Geoderma 267 (2016) 220–229

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Soil apparent conductivity measurements for planning and analysis of agricultural experiments: A case study from Western-Thailand

S. Rudolph [a,b,*], C. Wongleecharoen [c,d], R.M. Lark [b], B.P. Marchant [b], S. Garré [e,1], M. Herbst [a], H. Vereecken [a], L. Weihermüller [a]

[a] Forschungszentrum Jülich GmbH, Agrosphere Institute (IBG-3), Jülich, Germany
[b] British Geological Survey, Environmental Science Centre, Keyworth, England, United Kingdom
[c] Institute of Plant Production and Agroecology in the Tropics and Subtropics, University of Hohenheim, Germany
[d] Department of Soil Science, Kasetsart University Bangkok, Bangkok, Thailand
[e] Department of Earth and Environmental Sciences, Division Soil and Water Management, KU Leuven, Leuven, Belgium

ARTICLE INFO

Article history:
Received 19 January 2015
Received in revised form 3 December 2015
Accepted 13 December 2015
Available online 18 January 2016

Keywords:
Soil heterogeneity
Electromagnetic induction EMI
Soil apparent conductivity ECa
Experimental design
Power analysis

ABSTRACT

In experimental trials, the success or failure of agricultural improvements is commonly evaluated on the agronomic response of crops, using proper experimental designs with sufficient statistical power. Since fine-scale variability of the experimental site can reduce statistical power, efficiency gains in the experimental design can be achieved if this variation is known and used to design blocking, or some proxy variable is used as a covariate. Near-surface geophysical techniques such as electromagnetic induction (EMI), which describes subsurface properties non-invasively by measuring soil apparent conductivity (ECa), may be one source of this information. The motivation of our study was to investigate the effectiveness of EMI-derived ECa measurements for planning and analysis of agricultural experiments. ECa and plant height measurements (the response variable) were taken from an agroforestry experiment in Western Thailand, and their variability was quantified to simulate multiple realizations of ECa and the residuals of the response variable from treatment means. These were combined to produce simulated data from different experimental designs and treatment effects. The simulated data were then used to evaluate the statistical power by detecting three orthogonal contrasts among the treatments in the original experiment. We considered three experimental designs, a simple random design (SR), a complete randomized block design (CRB), and a complete randomized block design with spatially adjusted blocks on plot means of ECa (CRB_{ECa}). Using analysis of variance (ANOVA), the smallest effect sizes could be detected with the CRB_{ECa} design, which indicates that ECa measurements could be used in the planning phase of an experiment to achieve efficiencies by improved blocking. In contrast, analysis of covariance (ANCOVA) demonstrated that substantial power improvements could be gained when ECa was considered as a covariate in the analysis. We therefore recommend that ECa measurements should be used to characterize subsurface variability of experimental sites and to support the statistical analysis of agricultural experiments.

1. Introduction

Degradation of agricultural land by soil erosion has been recognized as a global challenge for food, feed, and fibre production (Purakayastha et al., 2011). The degree of land degradation is notably high in ecologically-sensitive regions with predominantly sloping uplands, highly erosive rainfall, and high population pressure (Garrity, 1993). A potential agricultural intervention to reduce soil erosion and to maintain soil fertility is seen in agroforestry where agricultural crops are intercropped with trees or perennials in the same management unit (Craswell et al., 1998; Garrity, 2004; Lal, 1989). Currently, the advantages and disadvantages of this land use management system are being examined worldwide.

In agricultural studies, the success or failure of management improvements is usually evaluated by estimating and testing differences among treatment means in a designed experiment. Sound experimental designs allow one to test treatment effects of interest with sufficient power. Statistical power is defined with respect to a treatment effect of specified magnitude and a threshold p-value (such as 0.05) for rejection of the null hypothesis of no effect. The power of an experiment and associated analysis is the probability that the null hypothesis would be accepted in a case where the specified treatment effect holds. All other factors being equal, power is increased by features of a design (e.g. blocking) which reduce the residual mean square substantially. It is common in experimental design to aim for power of 80% (e.g. Cohen,

* Corresponding author at: British Geological Survey, Environmental Science Centre, Keyworth, England.
E-mail addresses: s.rudolph@fz-juelich.de, sebrud@bgs.ac.uk (S. Rudolph).
[1] Now at the Université de Liège, Gembloux Agro–Bio Tech, Gembloux, Belgium.

http://dx.doi.org/10.1016/j.geoderma.2015.12.013
0016-7061/

1988). A review of the 30 most-cited papers reporting on alley cropping of maize, a common agroforestry practice, in the journal Agroforestry Systems from 1990 to 2010 illustrates that the complete randomized block design (CRB) is the most frequently used experimental design (68%) in agroforestry. The principle of CRB designs is to divide the experimental area into blocks which are internally as uniform as possible. Treatments are assigned at random to plots within blocks and the between-block variation is therefore removed from the residual in the data analysis, increasing the statistical power of the experiment. If blocking is to be successful then it should be based on some prior knowledge of the variation of the experimental site (Doncaster and Davey, 2007; Mead, 1991). However, agroforestry studies in the humid tropics are often carried out on newly established sites, where underlying soil properties or land management history are mostly unknown (Akondé et al., 1996; Chamshama et al., 1998; Jama et al., 1995). Only a few published studies made use of information from previous trials or soil sampling to guide the experimental design, and even in these cases it is questionable whether the amount of soil sampling was sufficient to characterize the site variability adequately. Solie et al. (1999) suggested that sampling soil and plant measurements at submetre intervals would be necessary for site characterization, which seems unrealistic. As an alternative, Corwin and Lesch (2003) proposed the use of non-invasive geophysical techniques to measure soil apparent conductivity (ECa) as a surrogate for primary and functional soil properties.

In precision agriculture, compact and lightweight electromagnetic induction (EMI) sensors have extensively been used to investigate the spatial variability of soil, and the resulting ECa measurements have been related to properties including clay content, soil water content, soil depth, nutrient status and crop performance (Eigenberg and Nienaber, 2003; Jaynes et al., 1995; Kachanoski et al., 1988; Kitchen et al., 2003; Robinson et al., 2012; Rudolph et al., 2015; Saey et al., 2009; Triantafilis and Lesch, 2005). Since EMI has rarely been used in small-scale agricultural experiments it is not possible, on the basis of currently-published research, to make any quantitative statements about the usefulness of EMI measurements for small-scale agroforestry experiments, and so to decide whether the costs of data collection are worthwhile. That is the motivation for this study. As well as using the EMI data in the analysis of a particular experiment we wanted to quantify the improvements in power which might be expected if EMI is incorporated into the design of an experiment, its analysis or both. This requires spatial modelling of the observations from our particular experiment to permit stochastic simulation of the results of experiments with different designs.

Our aims were: i) to characterize the soil variability of an established alley cropping experiment on a sloping upland using EMI-derived ECa measurements, ii) to investigate whether these measurements could assist the analysis of the particular experiment, and iii) to make a more general assessment of the effectiveness of ECa measurements in improving the power of such experiments using a stochastic model of the collected data.

2. Material and methods

2.1. Site description

The agroforestry experiment was carried out at the research station of Queen Sirikit's demonstration farm in Ratchaburi Province, Western-Thailand (13°28.2′N, 99°15.6′E, 160 m above sea level). Under a tropical monsoonal climate with a rainy season starting in June, a shallow soil was formed above weathered metamorphic bedrock, ranging from endoleptic Alisol to hyperskeletic Leptosols (IUSS Working Group WRB, 2007).

In 2009 the natural fallow vegetation along a steep hill slope was removed (0.2 ha) and 21 experimental plots were established. The plots (P01–P21) had a dimension of 4×13 m (52 m^2) with the shortest side along the contours. Plots were separated by at least 1 m, surrounded by concrete walls at three sides and were equipped with drip sprinklers for irrigation.

In a complete randomized block design with three replications (R1–R3) and six treatments (T1–T6) the effect of sequential addition of adapted agricultural improvements such as alley cropping, intercropping, tillage practice and N–P–K fertilization upon a maize monocrop system were investigated. Additionally, two bare soil plots (P17 and P20) and one monocrop chilli plot (P21) were established in R3. A detailed description of the experiment can be found in Hussain (2015). Maize (*Zea mays* L. ‘Pacific 999’) was sown at a spacing of 75 cm by 25 cm in rows along the contours at the end of June 2011. At the same time chilli (*Capsicum annuum* L. ‘Super Hot’) was transplanted with two plants per row at (T2–T6). Hedgerows of *Leucaena leucocephala* (Lam.) de Wit were planted in February 2009 in upper, middle, and lower position of T4 and T6 with an interhedgerow spacing of 5 m. The leguminous trees were regularly pruned to a width of 0.8 m and a height of 0.5 m while prunings were spread as mulch in the respective plots. The set-up of the experiment is illustrated in Fig. 1 and each treatment is briefly summarized in Table 1.

2.2. EMI measurements

Soil apparent conductivity was measured using the electromagnetic induction system EM38–MK2 (Geonics Limited, Ontario, Canada) in July 2011. The instrument is equipped with two receiver coils separated by 0.5 and 1.0 m from the transmitter. The respective depths of exploration (DOE) are 0.4 and 0.8 m for the vertical coplanar ($VCP_{0.5}$ and $VCP_{1.0}$) and 0.8 and 1.6 m for the horizontal coplanar ($HCP_{0.5}$ and $HCP_{1.0}$) mode. For general details on the operational and functional principles of EMI systems we refer to the work of McNeill (1980) as well as Corwin and Lesch (2003).

Prior to any plot measurements a system and operator calibration was performed as recommended by Sudduth et al. (2001), taking EMI readings along a calibration transect located in the bare soil plot P20 (see Fig. 1). Along this transect, additional electrical resistivity measurements (ERT) were performed using a Syscal Pro resistivity meter (IRIS instruments, France), as described by Garré et al. (2013), to calibrate the EMI readings, as suggested by Lavoué et al. (2010). This calibration was performed for a joint analysis of EMI data acquired on different measurement dates.

To achieve optimal sensor performance and to ensure repeatability and comparability of plot measurements under crop cover, EMI readings were taken manually in either *HCP* or *VCP* mode at predefined points separated 0.5 m from each other, by placing the instrument on the ground. Therefore, ropes marked with non-washable ink were oriented in transects along the slope or parallel towards the hedgerows resulting in 154 to 200 ECa measurements per plot. To minimize damage to the plant stand and to limit compaction of the topsoil, each plot was sensed only once except plots P01 and P20.

Soil temperature was recorded by ECH$_2$O-5TE sensors (Decagon, Pullman, USA) at 0.5 m depth and were used to standardize ECa measurements to a reference temperature of 25 °C (EC_{25}) by the approach of Corwin and Lesch (2005):

$$EC_{25} = EC_T \times \left(0.447 + 1.4034^{-T/26.815}\right) \tag{1}$$

where EC_T (mS m^{-1}) is the measured ECa at a particular soil temperature and T (°C) is the actual soil temperature on the measurement date. ERT-calibrated and temperature-corrected ECa measurements (expressed as ECa measurements hereafter) within a distance of 2 m to any plot-crossing cable connecting 66 Time Domain Reflectometry (TDR) sensors to record soil water content (SWC), or ECa values exceeding a predefined threshold, were removed. In addition, a spatial filter