Agricultural Water Management 210 (2018) 198–207

Contents lists available at ScienceDirect

Agricultural Water Management

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

A tree-bordered field as a surrogate for agroforestry in temperate regions: Where does the water go?

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ARTICLE INFO

Keywords:
Agroforestry
Electrical resistivity tomography
Soil moisture
Tree-crop-soil interactions

ABSTRACT

There is a renewed interest in temperate agroforestry systems because of their potential to increase biodiversity, sequester carbon and diversify the landscape while maintaining productivity. Little quantitative information is available about the interaction between trees and the crop for water, especially in temperate climate and for tree ages towards the end of an agroforestry cycle. With this study, we quantified the effect of mature poplar trees on soil moisture dynamics in space and time in an agricultural field sown with maize during one growing season. We confirmed the ability of electrical resistivity tomography to study tree-crop interactions for water under field conditions and we delimited an area of influence of the 40-year old trees on the crop of about 15 m. In order to do this, we installed four 30 m electrode transects perpendicular to the field border. Three transects were located next to a tree-bordered part of the field and one reference transect was located along the same border, but without any tree present. We performed seven electrical resistivity tomography (ERT) measurements during the maize growing season and compared the soil moisture distribution and dynamics with and without tree border as a proxy for a mature agroforestry system. We showed that the ERT tomograms in a tree-bordered zone are significantly different from a reference zone without trees along the 30 m of the transect using a single and segmented linear regression analysis. This article shows the potential of ERT to quantify tree-crop-soil interactions for water in agroforestry systems.

1. Introduction

During the last decade, there was a renewed interest in agroforestry systems in temperate climate because of their potential to increase biodiversity, sequester carbon and diversify the landscape (Borremans et al., 2016; Nair, 2007; Pardon et al., 2016; Torralba et al., 2016; Sanchez, 1995). A central hypothesis in the design of a performant agroforestry system states that the trees should acquire resources that would otherwise not be used by the crop (Cannell et al., 1996). Even though the number of projects studying agroforestry systems in the field is increasing lately (e.g. AGFORWARD, SAFE, TransAgroForest, AgroforestryVlaanderen.be, (non-exhaustive)), little quantitative information is available about the interaction between trees and the crop for water, especially in temperate climate. In most of the publications, trees and crop are in competition for water (Miller and Pallardy, 2001; Jose and Gillespie, 1998; Rao et al., 1997), especially where water availability is a limiting factor.

The main effect of trees on the soil water content (SWC) distribution in agroforestry systems is an increased depletion of soil moisture caused by the tree root water uptake in addition to the crop root water uptake. However, trees can also act as facilitators of water availability for the crop: the mechanism of hydraulic lift can increase soil moisture for the crop nearby the trees by the transport of water from deep moist soil to drier surface soil, through the root system of the trees (Burgess et al., 1998; Ong et al., 1998; Lambers et al., 1998). As the tree also creates shadow and can affect the micro-climate (e.g. relative humidity), its presence can reduce the evapotranspiration and therefore positively affect soil moisture. Other aspects might also increase the available SWC for crops like tree stem flow and deeper root water uptake (Pierret et al., 2007).

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https://doi.org/10.1016/j.agwat.2018.06.033
Received 16 July 2017; Received in revised form 12 June 2018; Accepted 26 June 2018

Different methods can be used to monitor soil water dynamics in agroforestry systems. Classical methods to measure SWC such as gravimetric measurements, neutron probes, time domain reflectometry or capacitance probes, are well known to provide correct and robust results. However, these methods give only local measurements of the SWC. Geophysical methods, and more specifically Electrical Resistivity Tomography (ERT) has proven to be a method avoiding some of the disadvantages mentioned above. ERT is minimally-invasive and results in a 2- or 3-D image of the soil electrical resistivity up to a few meters depth, depending on the electrode lay-out. Since the soil electrical resistivity is strongly linked to SWC (Zhou et al., 2001), this geophysical method is more and more applied to hydrological and soil sciences in a field called “hydrogeophysics”. ERT has been used to study solute transport (Kemna et al., 2002; Cassiani et al., 2006; Koestel et al., 2008; Garré et al., 2010)), water dynamics in cropped soil (Michot et al., 2003; Srayeddin and Doussan, 2009; Garré et al., 2013; Beff et al., 2013; Whalley et al., 2017), or orchard/trees (Ain-Lhout et al., 2016; Cassiani et al., 2015; Mares et al., 2016), showing that the technique has a lot of potential to provide data to complement classical agronomic experiments. This being said, ERT also has some limitations in respect of soil moisture monitoring: the decrease of resolution and sensitivity of the data with depth and the difficulty to investigate very dry soil because of the poor soil-electrode contact, the dependency of electrical resistivity to soil solution concentration (Moreno, 2014), and the sensitivity of the final SWC maps to inversion scheme and applied constraints. In addition, the need for independent soil water content data to establish a field-scale relationship between SWC and bulk soil resistivity remains. And even though different relationships have been applied to represent different soil horizons, the inherent spatial heterogeneity of this relationship because of soil heterogeneity in all dimensions has not been taken into account so far (Vanderborght et al., 2013). Pedo-electrical functions are less sensitive to bulk density changes than SWC.

In this paper, we aimed at quantifying the effect in space and time of mature poplar trees on the dynamics of soil electrical resistivity in an agricultural field sown with maize as a proxy for soil moisture dynamics. More specifically, we

(i) confirm the ability of electrical resistivity tomography to study tree-crop interactions under field conditions,
(ii) delimit an area of influence of the tree on the crop and study its characteristic during the growing season and
(iii) use the soil resistivity data to study the relationship between soil moisture dynamics and crop performance in this specific tree-bordered field experiment.

This study does not aim to give general conclusions about soil moisture dynamics in temperate agroforestry systems, but rather to give a proof-of-concept of complementary ways to study the tree-crop interactions for water using a specific case-study in Belgium.

2. Material and methods

2.1. Experimental site

The experiment was conducted in an agricultural field of 9.7 ha in Ypres, West Flanders, Belgium (50° 520 48.100 N lat, 2° 480 00.800 E long), during the growing season of 2016. The climate is temperate maritime. The soil type is a Luvisol (FAO, 2014). Table 1 gives the soil profile description as observed in a 90 cm deep soil pit followed by soil augering up to a depth of 180 cm. On 29th of March, 25 ton ha − 1 of pig manure was added to the field. The slurry was incorporated into the soil on April 30th. The field was ploughed (30 cm depth) the 6th of May and fertilized with 100 L of liquid N on May 8th. The maize (*Zea Mays L.*) was sown on May 9th, 2016 with a density of 110 000 plant ha-1 (row spacing of 75 cm and ca. 13 cm between plants in the row). The field was treated with herbicide the 20th of May and 1st of June (0.5 L ha-1 Laudis and 0.5 L ha-1 Stomp). Crop shortener was applied the 31st of June (1 L ha-1 Terpal). The plants were harvested on October 30th, 2016.

The experimental field is composed of two zones as shown in Fig. 1. The first one, the tree-bordered zone (TZ) (20 m × 30 m) is bordered by four 40-years old poplar trees (*Populus sp*) of about 19 m high and 5 m tree-to-tree spacing. The second one (5 m x 30 m) is a reference zone (RZ) without any tree, located at a distance of 50 m from the TZ. The TZ is used as a proxy for mature alley cropping systems, since those systems are practically unavailable in Belgium.

Using a single tree line of mature trees allows us to study the gradient in environmental and biotic variables from the tree line up to the open field. The orientation of the trees was N-E as is recommended for actual alley cropping fields, because it limits the duration of and crop area affected by shade for the crop to a minimum.

2.2. Field equipment

We acquired standard meteorological data (air temperature, air humidity, solar radiation, wind speed and rainfall) from a weather station from the Royal Meteorological Institute (RMI) network located in Beitem, at 20 km from the experimental field. In addition, we measured the same variables using a weather station installed in the field at 7 m from the tree line (see Fig. 1) to assess the impact of the dynamic shade created by the trees on the reference evapotranspiration. The in-field measurements were performed with a Mety2 weather station (Bodata, Dordrecht, the Netherlands). From these meteorological data, we calculated the reference evapotranspiration (ET0) using the FAO Penman-Montheith equation (Allen et al., 1998a) for full light and shade conditions. Note that the RMI station is located in standard conditions (well-watered grass), while the weather data of the in-field station are affected by crop evapotranspiration and differences in surface resistance due to the presence of the maize crop. On the other hand, tree rows in agroforestry systems also significantly affect the relative humidity and wind speed, due to a sheltering effect and the creation of a microclimate (Cleug, 1998; Jose et al., 2004). Therefore, ET_0 for the shaded situation was calculated in two ways: (1) with all data from the in-field station, and (2) with radiation data from the in-field station and relative humidity, wind speed, and air temperature from the RMI station. The crop evapotranspiration (ET_c) was subsequently calculated using the single K_c function approach for field corn (grain) under standard conditions as proposed by the FAO guidelines for computing crop water requirements (Allen et al., 1998a; Allen et al., 1998b). For the length of the crop development stages values from Idaho (USA) were used, and for Kc values for field corn were used.

Soil water matric potential at 15 cm depth was monitored hourly along three transects (TZ: two transects, RZ: one transect) at three distances from the tree line using Watermarks sensors (Irrometer Co., Riverside, USA) (see Fig. 1). Watermark sensors measure the electrical resistance of a granular matrix in which two electrodes are embedded, which can be related to the soil water potential using predetermined calibration curves. They are commonly used in irrigation scheduling and function in the range of -10 to − 100 kPa (Spaans and Baker, 1992; Whalley et al., 2001). Some limitations must be taken into account, such as a possible time lag between the real soil moisture change and the wetting of the matrix during rapid wetting or drying of the soil (McCann et al., 1992), the potential impact of soil solution concentration evolution, or the hysteretic relationship between water content and soil water potential (Whalley et al., 2001).

Soil temperature at 10 cm depth was registered with four 200TS temperature sensors (Irrometer Co., Riverside, USA) attached to the watermark datalogger (TZ: two sensors, RZ: two sensors). Four electrode transects of 30 m perpendicular to the tree line and crop rows were placed permanently in the field (TZ: three transects, RZ: one transect) in order to conduct electrical resistivity measurements. Fig. 1 gives an overview of the field site and location of the equipment.