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Framework for studying the hydrological impact of climate change in an alley cropping system

Dennis W. Hallema [a,b,*], Alain N. Rousseau [a], Silvio J. Gumiere [b], Yann Périard [b], Paul H. Hiemstra [c], Léa Bouttier [d], Maxime Fossey [a], Alain Paquette [e], Alain Cogliastro [d], Alain Olivier [f]

[a] Institut National de la Recherche Scientifique, Centre Eau Terre Environnement, 490 rue de la Couronne, Quebec City, QC G1K 9A9, Canada
[b] Université Laval, Département des sols et de génie agroalimentaire, 2480 boulevard Hochelaga, Quebec City, QC G1V 0A6, Canada
[c] S&T – Science and Technology Corp, PO Box 608, 2600 AP Delft, The Netherlands
[d] Institut de Recherche en Biologie Végétale, Université de Montréal, 4101 Sherbrooke East, Montreal, QC H1X 2B2, Canada
[e] Université du Québec à Montréal, Centre for Forest Research, PO Box 8888, Centre-ville Station, Montreal, QC H3C 3P8, Canada
[f] Université Laval, Département de phytologie, 2425 rue de l'Agriculture, Quebec City, QC G1V 0A6, Canada

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SUMMARY

Alley cropping is an agroforestry practice whereby crops are grown between hedgerows of trees planted at wide spacings. The local climate and the physiological adaptation mechanisms of the trees are key factors in the growth and survival of the trees and intercrops, because they directly affect the soil moisture distribution. In order to evaluate the long-term hydrological impact of climate change in an alley cropping system in eastern Canada, we developed a framework that combines local soil moisture data with local projections of climate change and a model of soil water movement, root uptake and evapotranspiration. Forty-five frequency domain reflectometers (FDR) along a transect perpendicular to the tree rows generated a two-year dataset that we used for the parameterization and evaluation of the model. An impact study with simulations based on local projections of three global and one regional climate simulation suggest that the soil becomes drier overall in the period between 2041 and 2070, while the number of critically wet periods with a length of one day increases slightly with respect to the reference period between 1967 and 1996. Hydrological simulations based on a fourth climate scenario however point toward wetter conditions. In all cases the changes are minor. Although our simulations indicate that the experimental alley cropping system will possibly suffer drier conditions in response to higher temperatures and increased evaporative demand, these conditions are not necessarily critical for vegetation during the snow-free season.

1. Introduction

Alley cropping is an agroforestry practice whereby agricultural, horticultural or companion crops are grown between hedgerows of trees or shrubs planted at wide spacings (Kang et al., 1981, 1984). The hydrological study of alley cropping is important for a variety of reasons. In the temperate and humid continental climate zone, alley cropping provides an alternative to traditional row cropping and reduces the impact of wind erosion and crop failure caused by excessive surface evaporation (*e.g.* Stigter, 1988). The practice is also used in the transition of traditional row cropping to foresting, and is acknowledged for its excellent stewardship qualities (Garrett et al., 2011). Alley cropping furthermore offers economic and social advantages, including diversification of income for farmers and improved recreational value (Jose, 2009), and it is estimated that the economic value of combined non-market services, such as water quality, air quality, climate regulation, and soil quality, is even higher than the value of marketable products such as agricultural products and timber (Alam et al., 2014).

Environmental benefits include higher carbon storage relative to traditional cropping systems (Montagnini et al., 2004; Nair et al., 2009), higher soil organic matter content (Bambrick et al., 2010), and reduced leaching of soil nutrients (Bergeron et al., 2011). Other studies report a higher bird and insect diversity in the intercrop area (Thevathasan and Gordon, 2004), increased presence of earthworms near the tree rows indicating good soil health (Price and Gordon, 1999), enhanced tree growth compared to forestry plantations (Rivest et al., 2009) and improved water

* Corresponding author at: Université Laval, Département des sols et de génie agroalimentaire, 2480 boulevard Hochelaga, Quebec City, QC G1V 0A6, Canada.
E-mail address: dennis-wesley.hallema.1@ulaval.ca (D.W. Hallema).

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quality (Jose, 2009). Alley cropping systems may also have a positive effect on soil biochemical properties and microbial resilience, which could potentially lead to improved crop yield and tolerance to water stress (Bairnard et al., 2012; Rivest et al., 2013).

To evaluate the long-term hydrological response of an alley cropping system it is necessary to have a proper understanding of the interactions between the different processes that are involved. Hydrologists have long known that soil water dynamics depend to varying degrees on local weather (precipitation, solar irradiance, temperature and wind), vegetation (distribution of the root system, growth stage), soil characteristics (texture, soil type, porosity) and upstream drainage area. Airflow near the land surface is influenced by the presence of a vegetation canopy (Wilson and Shaw, 1977), and therefore alley cropping has a direct effect on evapotranspiration and consequently on the soil water balance and water stress experienced by the intercrop planted between the tree rows. The local climate, which regulates the water input into the cropping system, and the physiological adaptation mechanism of the trees are key factors in the growth and survival of both the trees and intercrops. The water extraction mechanism of tree roots prolongs the water retention time in the upper layers of the soil, which increases the chance of survival for trees and intercrops and promotes growth even during dry spells (*e.g.* Plamboeck et al., 1999).

Southern Quebec in Canada is a region characterised by a humid continental climate, however a shift in the local climate will possibly result in increased periods of drought and higher rainfall intensities in the future (*e.g.* Mailhot et al., 2007). In this paper we present a hydrological framework for the distributed simulation of local hydrology in an experimental alley cropping system in southern Quebec, Canada. This framework allows us to conduct a climate impact study in which we evaluate whether this alley cropping system will experience more or less critically dry or wet episodes in the future period between 2041 and 2070 compared to the present day.

We adopted the following three-step approach:

1. Collection of distributed soil moisture data and soil texture data on the experimental alley cropping site during the snow-free season of 2011 and 2012 (present period); local weather measurements were used to generate local future climate projections for this site.
2. Parameterization and evaluation of a HYDRUS model (Šimůnek et al., 1992) of variably saturated flow in the soil underneath the alley cropping system, root uptake and potential evapotranspiration using data for the present period (2011 and 2012).
3. Hydrological projection for the period between 2041 and 2070, and comparison with simulations for a reference period between 1967 and 1996.

2. Experimental design

Measurements were performed at the St. Paulin experimental alley cropping site on the lower north shore of the St. Lawrence River in southern Quebec, Canada at 46°27′N 72°59′W. The section analysed in this study comprises two tree rows planted on opposing sides in the direction NE–SW (314°) with an intercrop area of 12.4 m × wide. One row is planted with *Populus deltoides* × *P. nigra* (hybrid poplar) spaced 2 m apart and the other with *Quercus rubra* L. (red oak) spaced 3.5 m apart, and both species were 9 years old at the time of this study. A forage mixture of *Phleum pratense* L. (millet) and *Trifolium pratense* L. (white clover) was sown in the intercrop area in 2009 (more details on the experiment in Bouttier et al., 2014). In order to parameterize the hydrological model, we collected data on soil moisture distribution, soil texture, root distribution and weather conditions.

2.1. Soil characteristics

Bambrick et al. (2010) classified the soil *in situ* as a dytric brunisol with pH 6.2 and moderate agricultural potential according to the Canadian Soils Classification System (Soil Classification Working Group, 1998). We sampled a vertical profile in the intercrop area and performed a grain size analysis based on the ASTM D-322 method (American National Standard Institute, 1972; McKeague, 1978). Organic matter content was determined by loss on ignition (LOI) at 375 °C according to the method described by the *Centre d'Expertise en Analyse Environnementale du Quebec* (CEAQ). The upper 75 cm the soil is mostly sandy (87–96% by weight) with smaller amounts of silt (2–8%) and clay (2–5%). A clay loam layer below 110 cm contains up to 34% clay, effectively reducing the hydraulic conductivity of the bottom of the profile. Organic matter content is highest in the upper 35 cm of the profile (2.9–3.6%).

2.2. Soil moisture monitoring using frequency domain reflectometry

Forty-five frequency domain reflectometers (FDR of the type 10HS manufactured by Decagon Devices) were used to monitor volumetric water content in the upper 100 cm of a transect perpendicular to the tree rows during the growing seasons of 2011 and 2012 (Fig. 1a). The sensors were subdivided into 11 sets of 2–5 sensors corresponding with one vertical profile each, and each sensor was inserted in a separate hand-drilled shaft with depths of 7, 25, 45, 75 and 100 cm. After insertion, the boreholes were filled with the original substrate.

FDR sensors of each set were installed at small distance intervals (20–25 cm) so that all sets combined provide an approximately two-dimensional soil moisture profile in the plane perpendicular to the tree rows. The FDR sensors use a unique frequency around 70 MHz, and have a volume of influence of 1 dm^3. The manufacturer specifies an accuracy of 0.02 $m^3\,m^{-3}$ (Decagon

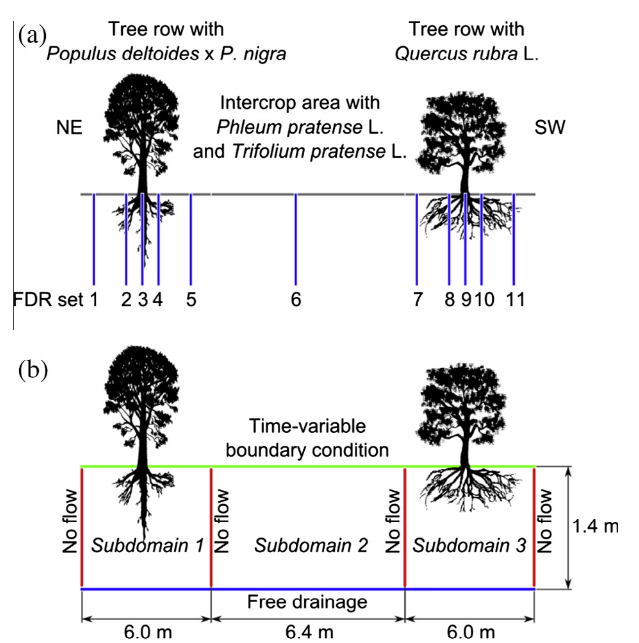

Fig. 1. (a) Transect of the FDR setup at the experimental alley cropping site. FDR sensors were divided into 11 sets along a line perpendicular to the tree rows. Each set contains 2–5 sensors installed at different depths. (b) Subdivision of the transect into three subdomains corresponding with the three vegetation types, which are from left to right *Populus deltoides* × *P. nigra*, forage (mixture of *Phleum pratense* L. and *Trifolium pratense* L.) and *Quercus rubra* L. (not drawn to scale) (tree silhouettes based on Leboeuf, 2007).