Science of the Total Environment 543 (2016) 862–876

Contents lists available at ScienceDirect

Science of the Total Environment

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

Remote sensing for mapping soil moisture and drainage potential in semi-arid regions: Applications to the Campidano plain of Sardinia, Italy

Rébecca Filion [a,*], Monique Bernier [a], Claudio Paniconi [a], Karem Chokmani [a], Massimo Melis [b], Antonino Soddu [b], Manon Talazac [a], Francois-Xavier Lafortune [a]

[a] *Institut National de la Recherche Scientifique, Centre Eau Terre Environnement (INRS-ETE), Quebec City, Canada*
[b] *Agenzia per la Ricerca in Agricoltura della Sardegna (AGRIS), Cagliari, Italy*

HIGHLIGHTS

- Regional soil moisture maps are derived from SAR C-band VV polarization data.
- Such maps can be integrated into water management tools in semi-arid regions.
- Surface soil moisture as low as 5% was monitored with C-band SAR on bare soil.
- LANDSAT TM5 soil moisture regional maps were not accurate.

ARTICLE INFO

Article history:
Received 28 January 2015
Received in revised form 10 July 2015
Accepted 14 July 2015
Available online 5 August 2015

Keywords:
Soil moisture
SAR C-band imagery
LANDSAT imagery
Remote sensing
Agriculture
Hydrology

ABSTRACT

The aim of this study is to investigate the potential of radar (ENVISAT ASAR and RADARSAT-2) and LANDSAT data to generate reliable soil moisture maps to support water management and agricultural practice in Mediterranean regions, particularly during dry seasons. The study is based on extensive field surveys conducted from 2005 to 2009 in the Campidano plain of Sardinia, Italy. A total of 12 small bare soil fields were sampled for moisture, surface roughness, and texture values. From field scale analysis with ENVISAT ASAR (C-band, VV polarized, descending mode, incidence angle from 15.0° to 31.4°), an empirical model for estimating bare soil moisture was established, with a coefficient of determination (R^2) of 0.85. LANDSAT TM5 images were also used for soil moisture estimation using the TVX slope (temperature/vegetation index), and in this case the best linear relationship had an R^2 of 0.81. A cross-validation on the two empirical models demonstrated the potential of C-band SAR data for estimation of surface moisture, with and R^2 of 0.76 (bias +0.3% and RMSE 7%) for ENVISAT ASAR and 0.54 (bias +1.3% and RMSE 5%) for LANDSAT TM5. The two models developed at plot level were then applied over the Campidano plain and assessed via multitemporal and spatial analyses, in the latter case against soil permeability data from a pedological map of Sardinia. Encouraging estimated soil moisture (ESM) maps were obtained for the SAR-based model, whereas the LANDSAT-based model would require a better field data set for validation, including ground data collected on vegetated fields. ESM maps showed sensitivity to soil drainage qualities or drainage potential, which could be useful in irrigation management and other agricultural applications.

1. Introduction

1.1. Impact of climate change in the Mediterranean region

According to a recent World Bank report (WorldBank, 2014), global temperatures are 0.8 °C above pre-industrial temperatures. Based on past greenhouse gas emissions and current trends, a further atmospheric warming to 1.5 °C above pre-industrial levels is expected in the short term. In absence of concerted action to reduce emissions, global warming is expected to be around 2 °C by 2050 and 4 °C by 2100. No region will be spared from this change and the adverse effects of this phenomenon will be felt on agriculture, water resources, ecosystems, and human health, especially in regions that are already the most vulnerable, such as semi-arid areas.

Proper water resources management is important in reducing vulnerability to drought and other extreme events that may occur with increasing frequency as a consequence of climate change. Arid and semi-arid regions of the Mediterranean basin are already significantly affected by climate change according to the fifth report of the Intergovernmental Panel on Climate Change (IPCC, 2014). It is expected that these regions will become drier and warmer, thus putting even more pressure on already vulnerable water resources (Dong et al., 2013; IPCC, 2007; Ludwig et al., 2011; Olesen et al., 2011; WorldBank,

---

[*] Corresponding author.
E-mail address: rebecca.filion@ete.inrs.ca (R. Filion).

http://dx.doi.org/10.1016/j.scitotenv.2015.07.068

2014). Uncertainties regarding the safety of fresh water (scarcity and quality) are a major concern for the entire Mediterranean region. Changes in the hydrological cycle will lead to an increasing risk of tension and conflict in social, ecological, political, and economic spheres (Dong, 2011; Garcia-Ruiz et al., 2011; Ludwig et al., 2011). Development and implementation of effective adaptation and preventive policies requires interdisciplinary collaboration and exploitation of advanced technologies for environmental monitoring, modeling, and analysis.

1.2. Importance of surface soil moisture and soil drainage for hydrological modeling and agricultural management

In water resources management, surface soil moisture (SM) is an essential state variable and plays a crucial role in various hydrological processes (Islam and Engman, 1996). SM influences the planetary boundary layer structure and heat flow because it controls interactions between the land surface and the atmosphere, such as infiltration, retention, runoff, percolation, and evapotranspiration (Bandara et al., 2014; Pierdicca et al., 2014; Seneviratne et al., 2010). Soil drainage quality is an important property that influences the temporal and spatial variations of surface SM and the vulnerability of soils to degradation and desiccation, which directly affects plant growth (Niang et al., 2006).

Monitoring spatial and temporal variations of SM as well as other land surface characteristics is essential to many hydrological and agricultural applications. Surface SM is one of the main inputs to hydrological models, used in updating the model's boundary conditions and in driving surface and subsurface partitioning of water and energy fluxes (Camporese et al., 2009; Niu et al., 2014). Timely detection of soil drying conditions can help improve the use of irrigation water, augment agricultural production, and provide early warning of drought conditions. This information can be very useful for water and agricultural management at regional scale.

1.3. Potential of remote sensing for soil properties retrieval

The potential of remote sensing to obtain information on soil properties in the fields of hydrology and water resources management at local and regional scale is recognized since the 70s (Batlivala and Ulaby, 1976; Kornelsen and Coulibaly, 2013; Obade and Lal, 2013; Ochsner et al., 2013; Rast et al., 2014; Shoshany et al., 2013).

Satellites operating in the visible and near infrared use light energy from the sun reflected on the objects. The data acquired in these parts of the electromagnetic spectra can be used to observe soil properties based on the temperature/vegetation index (TVX), which depends on the surface SM (Wang and Qu, 2009). TVX is a relationship between the resistance of the land to evaporation and SM across the slope of the space Land Surface Temperature (LST)/Normalized Vegetation Index (NDVI) (Carlson, 2007; Carlson et al., 1994).

Sensors operating in microwave frequencies, such as radar, transmit and receive a signal and can be used at night and in the presence of clouds. The backscatter signal from radar sensors depends on the interaction between SM, topography, surface roughness, and the amount/type of plant cover. Despite the challenge to isolate the contribution of SM from the other surface properties, the radar signal is sensitive to the dielectric constant of the soil which is a function of soil humidity (CCRS, 2014). The most used theoretical models for retrieving SM are the Integral Equation Model (IEM) (Fung, 1994) and the Advanced Integral Equation Model (AIEM) (Wu et al., 2008), which are applicable over a wide range of soil roughness. The most commonly used semi-empirical models are Oh et al. (1992) and Dubois et al. (1995), which provide analytical relationships between the backscattered radar signal and the physical parameters of the soil derived from experimental data (Wang and Qu, 2009). Finally, empirical models are based on experimental measurements to establish relationships for retrieving SM from backscatter observations (Wang and Qu, 2009). They are generally derived from specific data, for a given place, and often are valid for a certain frequency, a certain angle of incidence, and a range of soil roughness and moisture content (Dubois et al., 1995). The main advantage of empirical models, compared to theoretical models, is that many natural areas are not part of the theoretical model's region of validity (Oh et al., 1992; Wang and Qu, 2009).

The parameters of the radar system can help to retrieve SM. Firstly, the incidence angle must be as low as possible in order that the backscattered signal is minimally influenced by vegetation or soil roughness (Baghdadi et al., 2006; Lakhankar et al., 2009). Secondly, radar sensors operating in L-band have the advantage of being able to penetrate the soil more deeply (20 cm). However, the majority of the literature is from radar systems operating in C-band (more available data) which penetrates the first five centimeters of the ground surface (Alvarez-Mozos et al., 2009; Baghdadi et al., 2012; Balenzano et al., 2011; Moran et al., 2004; Paloscia et al., 2013; Wagner et al., 2012). Thirdly, polarization (orientation of the electromagnetic wave) influences the backscattering signal received. Some research reports good results with a given polarization (Lievens and Verhoest, 2012; Zribi et al., 2011) while others justify the use of multi-polarization (copolarization or depolarization) (Holah et al., 2005; McNairn and Brisco, 2004). Therefore, results depend on available data and the study site, and it is thus important to test each polarization and polarization ratio for a given site. Finally, the time at which the image is acquired can have an influence on the signal since surface soil moisture can vary between morning and evening orbit.

1.4. Objectives, goal, and hypothesis

Radar and optical/thermal satellite data have already proven their potential to estimate surface SM and pedological maps are already used to establish drainage qualities of dominant soils. The hypothesis of this research is that satellite images will help identify very well and very poorly drained soils for an entire agricultural plain in a semi-arid environment, even during drought periods. In this context, the goal of this research is to investigate the potential of empirical relationships between remotely sensed signals (radar backscatter or optical reflectance and thermal emission) and SM values measured at the field scale in order to produce maps of estimated SM, and to identify very well and very poorly drained areas, across an agricultural plain in a semi-arid region in Sardinia (Italy). The methodology is based on multiple scale data collected from 2003 to 2009: ENVISAT ASAR (Advanced Synthetic Aperture Radar), RADARSAT-2, and LANDSAT TM5 satellite imagery from 2003 on; ground data collected at the field plot scale from 2005 on; and pedological and other information from regional maps.

2. Study site and ground data

2.1. Study site

Sardinia is located approximately 8°E–10°E and 39°N–41°N, in the center of the Mediterranean Sea, and has a total area of 24 000 km^2 (Fig. 1).

Intensive field campaigns to acquire ground data were undertaken at the Azienda San Michele, an agricultural research center run by AGRIS (Agenzia della Regione Sardegna per la ricerca scientifica) and covering an area of 4.36 km^2. This farm is part of the Rio Mannu di San Sperate basin. The basin drains an area of 472.5 km^2 and is located in the southern part of the island of Sardinia, in the Campidano plain, the island's most important agricultural area with an approximate area of 3 000 km^2 (Pungetti, 1995). The Campidano plain is very fertile and is cultivated especially with cereal grains, olives, fruits, vegetables, and vineyards. The CORINE land use/land cover classification (EEA, 1995) has been used to delimit the agricultural area (arable land, permanent crops, pasture, and heterogeneous agricultural areas) of the Campidano plain, which is the regional scale study area for this study. In Fig. 1,