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Analysis of TerraSAR-X data sensitivity to bare soil moisture, roughness, composition and soil crust

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ABSTRACT

Soils play a key role in shaping the environment and in risk assessment. We characterized the soils of bare agricultural plots using TerraSAR-X (9.5 GHz) data acquired in 2009 and 2010. We analyzed the behavior of the TerraSAR-X signal for two configurations, HH-25° and HH-50°, with regard to several soil conditions: moisture content, surface roughness, soil composition and soil-surface structure (slaking crust).

The TerraSAR-X signal was more sensitive to soil moisture at a low (25°) incidence angle than at a high incidence angle (50°). For high soil moisture (>25%), the TerraSAR-X signal was more sensitive to soil roughness at a high incidence angle (50°) than at a low incidence angle (25°).

The high spatial resolution of the TerraSAR-X data (1 m) enabled the soil composition and slaking crust to be analyzed at the within-plot scale based on the radar signal. The two loamy-soil categories that composed our training plots did not differ sufficiently in their percentages of sand and clay to be discriminated by the X-band radar signal.

However, the spatial distribution of slaking crust could be detected when soil moisture variation is observed between soil crusted and soil without crust. Indeed, areas covered by slaking crust could have greater soil moisture and consequently a greater backscattering signal than soils without crust.

1. Introduction

Floods, drought and erosion are major issues for risk assessment. In the context of sustainable development, soil management is important for environmental and socioeconomic applications. Hence, there is a need for continuous information about key soil parameters to predict and understand these natural hazards (Wu & Wang, 2007). Slaking crust (the disintegration of plowed clods) is a key factor that controls runoff and erosion because of its influence on infiltration capacity (Casenave & Valentin, 1992; Govers et al., 2000; King & Le Bissonnais, 1992; Le Bissonnais & Singer, 1992). Similarly, by conditioning the distribution of rainfall between infiltration, surface retention and runoff (Auzet et al., 2005; Cerdan et al., 2006; Valentin et al., 2005), soil moisture and surface roughness play an important role in risk assessment (Loumagne et al., 1991; Loumagne et al., 2001; Oudin et al., 2003). Nevertheless, monitoring and modeling these soil surface characteristics remain difficult because of their substantial variation over space and time (Boiffin et al., 1988; Zobeck & Onstad, 1987).

In this context, satellite imagery is a powerful tool that can provide accurate and repetitive spatial data. Synthetic-aperture radar (SAR) techniques are particularly useful because they make it possible to monitor soil parameters under any weather conditions (Dobson & Ulaby, 1986; Fung, 1994; Hallikaïnen et al., 1985; Ulaby et al., 1986). For bare agricultural soils, the backscattered radar signal depends strongly on the geometric characteristics (roughness) and dielectric properties (moisture content, soil composition) of the soil. Many studies using data collected by space and airborne SAR scatterometers and model simulations have already shown the potential of radar data to retrieve soil parameters (roughness and moisture) (Baghdadi, Cerdan, et al., 2008; Baghdadi et al., 2002; Baghdadi et al., 2006; Baghdadi et al., 2007; Dobson & Ulaby, 1986; Fung & Chen, 1992; Holah et al., 2005; Le Hégarat Mascle et al., 2002; Oh, 2004; Shi et al., 1997; Srivastava et al., 2003, 2009; Ulaby et al., 1978; Zribi et al., 2005; Zribi & Dechambre, 2002).

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Whatever the SAR configuration, the radar signal follows a logarithmic function with the soil-surface roughness (Fung, 1994; Ulaby et al., 1986). Ulaby et al. (1978) have shown that the influence of surface roughness decreases with increasing radar frequency. The dynamics of the relationship between the radar signal and roughness parameter are stronger in the L-band than in the C- and X-bands (Baghdadi et al., 2008; Ulaby et al., 1986) Moreover, SAR data are more sensitive to soil roughness at high incidence angles (Baghdadi, Cerdan, et al., 2008; Baghdadi, Zribi, et al., 2008; Zribi & Dechambre, 2002).

The SAR signal increases with increasing soil moisture for values between 0 and 35–40% (Baghdadi et al., 2007; Holah et al., 2005). Beyond this threshold, the backscattering coefficient becomes constant and then decreases with increasing soil moisture (Holah et al., 2005). Several studies in the C-band, with the SAR configuration fixed at a single polarization, have shown that the sensitivity of the radar signal to soil moisture is greater at low and medium incidence angles than at high incidence angles (approximately 0.2 dB/% for HH-20°–37° and approximately 0.1 dB/% for HH-39°) (Baghdadi, Cerdan, et al., 2008; Baghdadi et al., 2006; Beaudoin et al., 1990; Srivastava et al., 2003; Zribi & Dechambre, 2002).

However, few studies have been conducted in the X-band. The first results based on microwave measurements in the X-band have shown that an incidence angle of 25° is appropriate to observe soil moisture (Singh, 2005). For the TerraSAR-X sensor, Paris Anguela et al. (2010) have found that the sensitivity of the radar signal to soil moisture is approximately 0.35 dB/% for the HH-25° configuration.

The surface area of soil particles in a soil depends on the particle sizes which control the percentage of free and bound water (Srivastava et al., 2009). Few studies have analyzed the response of the radar signal to soil composition in terms of grain-size distribution (percentages of sand and clay). The grain-size distribution has an effect on dielectric behavior over the entire frequency range (1.4 to 18 GHz) and is most pronounced at frequencies below 5 GHz (Hallikaïnen et al., 1985). In the C-band, decreasing soil clay content increases the sensitivity of the radar signal to soil moisture (0.22 dB/% for clay soil: 49% clay, 35% silt and 16% sand; 0.33 dB/% for loamy soil: 17% clay, 48% silt and 35% sand) (Ulaby et al., 1978). Because the distribution of grain sizes controls the amount of free water that interact with the incident microwave, the amount of free water gives significant contribution to SAR backscatter (Srivastava et al., 2006, 2009).

In the X-band at HH polarization, Prakash et al. (2009) have shown a relationship between the specular scattering coefficient for bistatic scatterometer data and the sand percentage in the soil when surface roughness is less than 1.4 cm. For one plot and one TerraSAR-X acquisition (HH-25°), Paris Anguela et al. (2010) have also shown that a soil with a smaller percentage of clay (soil B: 17% clay, 79% silt and 4% sand) had a TerraSAR signal (HH-25°) 3 dB stronger than that of a more clayey soil (soil A: 32% clay, 64.5% silt and 3.5% sand). The driest upper millimeters of soil B and the low X-band penetration at high moisture content (Nolan & Fatland, 2003) were used to explain the difference in signal between soil B and soil A.

Because soil slaking depends primarily on material properties (moisture, organic-matter content and carbonate content) and decreases infiltration rates, the backscattered radar signal may be sensitive to this soil parameter. Nevertheless, few studies have examined the effect of soil slaking on the radar signal. In the X-band, Stolp and Janse (1986) have carried out a multiple linear regression to relate the backscattering coefficient (HH-15°) to the degree of slaking, the direction of tillage and the incidence angle. Their results are promising and provide good estimates of the degree of slaking (with an accuracy between 78% and 56%).

Finally, soil parameters are usually estimated from SAR imagery at plot or watershed scales. Few studies have been conducted at the within-plot scale. In fact, the speckle effects and low resolution (between 10 and 30 m) of the first-generation SAR data (ERS, RADARSAT-1 and ASAR) prevented the analysis of small-scale variations. The high spatial resolution of the TerraSAR-X sensor (1 m) provides access to soil-surface heterogeneities at a finer scale. Baghdadi, Zribi, et al. (2008) have already mentioned signal variations from TerraSAR-X images within agricultural plots. Quantitative analysis was not conducted, but only observations were given from photo-interpretation of SAR images. Paris Anguela et al. (2010) have made a preliminary diagnostic with an analysis from only one bare agricultural plot and in using only one TerraSAR image. In the present work we consolidated and completed these previous investigations in using large database of in situ measurements (soil composition, soil moisture and observations concerning the presence or the absence of crust) and TerraSAR-X images at different radar incidence angle.

The main objective of this study is to analyze the potential of the TerraSAR-X radar sensor to characterize soil-surface parameters at the plot and within-plot scales. The effects of soil moisture, roughness, soil composition and slaking crust on the TerraSAR-X backscattering coefficient are analyzed only over agricultural plots.

2. Material and methods

2.1. Study site

The study site is the Orgeval watershed (104 km²), which is located to the east of Paris (France; 48°51′N 3°07′E; Fig. 1). The site has been managed since 1962 as an experimental basin for hydrological research by the Agricultural and Environmental Engineering Research Center (CEMAGREF) research institute. The Orgeval watershed is mostly composed of agricultural plots intended for growing wheat and maize. It is flat and composed of loamy soils with average percentages of 17% clay, 78% silt, and 5% sand. This soil structure promotes crust development, which increases soil sealing and causes runoff (Boiffin et al., 1988; Eimberck, 1990).

2.2. Satellite data

2.2.1. SAR data

Fourteen TerraSAR-X images (X-band) were acquired in 2009 and 2010 in Spotlight mode (pixel spacing ~1 m) with HH polarization and incidence angles of 25° and 50°. The incidence angles of each TerraSAR image are summarized in Table 1.

Fig. 1. Location of the Orgeval watershed (France; central coordinates: 48°51′N, 3°07′E).