Exploring the use of synthetic aperture radar data for irrigation management in super high-density olive orchards

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ABSTRACT

Understanding the plant water-uptake dynamics and behavior in olive orchards is an area of much interest, particularly for efforts to optimize the use and application of water resources. However, plant water-uptake information is rarely available or consistently monitored for large agricultural areas, especially in developing countries. Here we evaluate the potential of using synthetic aperture radar (SAR) images to monitor the water-uptake rate in super high-density olive orchards located in the hot and arid desert climate of Saudi Arabia. The experiment was performed using Sentinel-1 data acquired between 2019 and 2020 in concert with in situ sap flow measurements. To date, no study has explored the potential of Sentinel-1 SAR data to assess the water-uptake rate in olive orchards. The results demonstrate that the SAR backscatter increased between January and July/August, and then decreased during the remainder of the year, following a broadly Gaussian distribution. Of key interest is the strength of the relationship between the increasing and decreasing trends of SAR backscatter and the variation in the coincident water-uptake rate measured in situ, producing a coefficient of determination of 0.81 in the VV polarization. As the relationship between the SAR backscatter and water-uptake rate was established for plots with similar tree type and planting density, further exploration of orchards with different characteristics and planting densities is needed to fully understand the potential of SAR data to estimate plant water-uptake. Overall, the study demonstrates that SAR data can track variation in locally measured water-uptake and illustrates the potential to assist with enhancing irrigation management.

1. Introduction

Irrigation in olive orchards reduces water stress and allows trees to absorb more nutrients, which increases olive productivity (Bustan et al., 2016). To improve yield through water volume rationing, farmers often apply Regular Deficit Irrigation (RDI) throughout the growing season. For instance, Fernández et al. (2013) reported that the RDI technique applied to super high density Arbequina olive trees in Spain saved 72% water, while only decreasing the yield by 26%. In its most basic implementation, RDI applies a percentage of a crops evapotranspiration determined of 0.81 in the VV polarization. As the relationship between the SAR backscatter and water-uptake rate was established for plots with similar tree type and planting density, further exploration of orchards with different characteristics and planting densities is needed to fully understand the potential of SAR data to estimate plant water-uptake. Overall, the study demonstrates that SAR data can track variation in locally measured water-uptake and illustrates the potential to assist with enhancing irrigation management.

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oriented perpendicular to the direction of the SAR viewing angle (McDonald et al., 1990). Furthermore, SAR ensures consistent and repeated observations due to day and night imaging and cloud penetration capabilities.

In theory, variations of microwave backscatter from mature evergreen tree canopies are primarily related to variation in canopy absolute moisture content (Cermak et al., 2007; Way et al., 1990). Numerous studies have investigated the potential of microwave backscatter to infer the diurnal and seasonal variation in the dielectric constant of forest canopies (Magagi et al., 2002; Paget et al., 2016; Pulliainen et al., 2004; Rao et al., 2020). For instance, Paget et al. (2016) used microwave data acquired twice a day from the Rapidscat satellite and reported significant diurnal variations in backscatter across several forest types. Froliking et al. (2011) reported a decrease in backscatter from the SeaWinds satellite over the southwestern Amazon forest during the 2005 drought. Friesen (2008) reported significant diurnal differences from the ERS 1/2 satellites over West Africa. While these studies have focused on forest (Steele-Dunne et al., 2012), one recent study explored the behavior of C-band SAR backscatter data over irrigated olive orchards (density of one tree every 5 × 5 m²) (Chakir et al., 2021). In that analysis, Sentinel-1C-band backscatter (45°) showed a Gaussian behavior with an increase between January and July/August and a decrease for the rest of the year. While some satellite studies have been performed, relatively limited research has been conducted using ground based scatterometers to investigate the potential of microwave backscatter to assess changes in the diurnal dielectric constant of trees (Heiska and Hallikainen, 1994; McDonald et al., 1990; van Emmerik et al., 2015; Way et al., 1991). In a study over a walnut orchard in the San Joaquin Valley of California, Way et al. (1991) reported that large diurnal variations in the tree dielectric properties produce significant diurnal changes in the microwave backscatter. The results of their 2-week experiment showed diurnal oscillations in the backscatter for L-, C-, and X-bands at a high incidence angle. For C-band in vertical transmit and vertical receive (VV) and in horizontal transmit and vertical receive (HV) polarization, the backscatter increased about 2 dB from midnight to the afternoon. Similarily, Heiska and Hallikainen (1994) reported a diurnal behavior in C-band backscatter (40° incidence angle) over pine trees, with transpiration believed to cause water fluctuation within trees and, therefore, a periodicity in the behavior of the tree water content and associated microwave backscatter. In contrast to Heiska and Hallikainen (1994), Way et al. (1991) reported an increasing trend for the diurnal backscatter, which may relate to the sensitivity of backscatter data to canopy structure. Indeed, Macelloni et al. (2001) reported that SAR backscatter increases with an increase in the biomass (and hence water content) for broad-leaved trees (where scattering mechanism is likely dominant), whereas for narrow-leaved trees, SAR backscatter decreases with biomass (i.e. attenuation mechanism is dominant).

There are numerous studies supporting the result that seasonal and diurnal variation of microwave backscatter at different frequencies may be due to variation in water-uptake dynamics (Friesen et al., 2007; Friesen, 2008; Paget et al., 2016; Way et al., 1991). Indeed, since canopy water status is driven by water-uptake (Heiska and Hallikainen, 1994; van Emmerik et al., 2015) and SAR backscatter is sensitive to canopy water status (Cermak et al., 2007; Way et al., 1990), SAR data may therefore represent a potential means to monitor water-uptake. However, uncertainty still surrounds the relationship between water-uptake and observed backscatter (Froliking et al., 2011; McDonald et al., 2002; Paget et al., 2016; Steele-Dunne et al., 2013). To date, no study has directly evaluated the relationship between SAR backscatter and water-uptake rate variations in olive orchards using time-series of in-situ measurements of water-uptake. In this study, we undertake an exploratory analysis of the temporal variation of Sentinel-1C-band SAR data for a 2-year period over super high-density olive orchards located in the Al-Jawf region of Saudi Arabia. The main objective was to explore the potential of SAR data to assess the water-uptake rate via its impact on canopy moisture variation. To do this, the dynamics of SAR data over the study period were analyzed for 52 olive plots, and a correlation between SAR data and the in situ measured water-uptake rate was explored over three plots containing permanent installations of sap flow meters. Finally, the assessed relationship between SAR backscatter and field-measured water-uptake rates was evaluated in relation to information on ground irrigation practices, as irrigation is a key factor in the water-uptake process.

2. Data and methodology

2.1. Description of the study site

The study focused on an olive farm located in the Al-Jawf region of Saudi Arabia (29.8° N, 38.4° E) (Fig. 1). The farm represents one of the world’s largest olive orchards, with 6 million trees of three main varieties (Arbequina, Arbosana and Koroneiki). The planting density of the olive tree plots is one tree per 6 m², i.e. 1667 trees/ha, where trees are planted 1.5 m apart in rows with 4 m between each row. The olive trees were planted between 2010 and 2017. Trees are pruned to maintain a height in all plots of between 2 and 3 m with a rooting depth that ranges from 0.5 to 1.0 m. Each tree receives water from a drip irrigation system that supplies water within a radius of 40 cm around the trunk. In order to ensure a representative selection of plots to assess SAR backscatter behavior over the olive orchards, 52 different plots (between 2.5 and 4.0 ha each) of very high-density olive trees were selected (Fig. 1).

A permanent weather station is installed at the site (see Plot 50, denoted by a black star in Fig. 1b) that collects standard meteorological measurements and heat fluxes. In 2019 and 2020, the maximum daily average wind speed at the site was 3.9 m/s, while average daily air temperature increases from 5 °C in January to about 30 °C in July/August (Fig. 2). Maximum air temperature reaches up to 44 °C in July/August. Typical of the region, rain events are rare, with a maximum daily rainfall of 3.8 mm and a cumulative rainfall between January 2019 and December 2020 of 44 mm (Fig. 2).

2.2. Sap flow meter for water-uptake measurements

Measuring the diurnal and seasonal variations in tree water-uptake helps to understand soil-plant-atmosphere interactions and provides insight into irrigation management (Jackisch et al., 2020). A sap flow meter (SFM) is a stand-alone instrument measuring the sap flow rate (i.e. water-uptake rate) of trees. The system employed here is the SFM1 from ICT international Pty Ltd, which uses the principle of the Heat Ratio Method (Burgess et al., 2001; Marshall, 1958) to measure high, low and reverse flow rates in both small woody stems and roots as well as in large trees. Each device consists of three needles, where the middle needle acts as a heating element and the upper and lower needles contain outer and inner thermistors (Fig. 3). All needles are 35 mm long and were inserted on the main stem such that the outer thermistor is 2.5 mm inside the sapwood (Fig. 3c).

Seven SFM instruments were installed in 2019 and 2020 in Plots 50 (4 SFMs in 2019), 30 (2 SFMs in 2020), and 31 (1 SFM in 2020), with each device installed approximately 30 cm from the soil surface. A full year of data was able to be obtained from SFMs installed in Plots 30 and 31 in 2020, while SFMs inside Plot 50 operated for only 4 months in 2019. The trees selected for SFM installation were located away from the plot edges and had similar height, age, condition, canopy structure, and trunk diameter as the majority of the olive trees within the three plots. All trees belonging to one plot are relatively homogenous and irrigated at the same time with a drip irrigation system. Thus, for a given plot, it was assumed that the measured water-uptake rate of the selected trees was similar to the majority of trees occurring within that plot. The water-uptake rate from SFMs was computed at 10-minute intervals using the Sap Flow Tool software (ICT International Pty. Ltd). For Plots 30 (2 SFMs) and 50 (4 SFMs), the water-uptake rate records of all SFMs were
averaged for each plot. Water-uptake rate ranges from 0.2 to 1.6 L per hour (L.h\(^{-1}\)) (Section 3.1).

2.3. Soil moisture data

Two HydraProbe soil moisture sensors from Stevens Water (https://stevenswater.com/products/hydraprobe/) were installed in Plot 50 in 2019 and 2020 to collect soil moisture measurements at 10 cm and 30 cm depth at a 15-min time intervals. In addition to measuring soil moisture, these sensors were used to detect the presence of irrigation activity via interrogation of the high-temporal resolution data. The soil moisture measurements at 10 cm ranged between 0.10 and 0.42 [cm\(^{-3}\).cm\(^{-3}\)] and soil moisture measurements at 30 cm varied between 0.04 and 0.30 [cm\(^{-3}\).cm\(^{-3}\)].

2.4. Satellite-based synthetic aperture radar data

SAR data were acquired by Sentinel-1A and Sentinel-1B with a 6-day revisit time between January 2019 and December 2020 at approximately 1832 KSA local time. A high incidence angle is needed to preclude backscatter from bare ground in between tree rows (i.e. to ensure backscatter was mainly from the tree canopy) (McDonald et al., 1990). In this case, relative orbit number 14 provided an incidence angle of approximately 42° to satisfy this requirement. In total, 122 Sentinel-1 images were acquired using the Google Earth Engine (GEE) platform. GEE provides Sentinel-1 Level-1 Ground Range Detected (GRD) scenes processed to backscatter coefficient (\(\sigma^0\)) in decibels (dB) (see https://developers.google.com/earth-engine/guides/sentinel1 further details). GEE employs the preprocessing steps, including orbit file application, GRD border noise removal, thermal noise removal, radiometric calibration, and terrain correction (orthorectification). More details on these processing steps can be found in the study by Filipponi (2019).

Fifty-two plots of super high-density olive trees geographically distributed throughout the olive areas within the farm were selected to carry out the experiment. Plots selection was made manually in order to...
have samples from all the places where there are olives in the study site (Fig. 1). The temporal behavior of C-band SAR backscatter was extracted from SAR images separately for each plot. For each plot, the SAR backscatter at a given acquisition date was computed as the average of the pixel values (linear unit) located in that plot, and used for assessment of temporal dynamics of the SAR backscatter. The extracted SAR temporal profile was later smoothed using a Gaussian filter to eliminate fluctuation that can be caused by environment factors (e.g. rain) or agriculture practices (Nasrallah et al., 2019; Song and Wang, 2019; Vavlas et al., 2020). The SAR backscatter and the associated Gaussian smoothing were then compared to simultaneous water-uptake measured from the SFMs, with the coefficient of determination ($R^2$) computed. The relationship between SAR backscatter and water-uptake rate measured by the SFMs was explored for the three plots, where SFMs are installed. To assess the temporal behavior of C-band SAR backscatter more broadly over the olive orchards of the study site, the C-band behaviors were analyzed for the 52 selected plots.

![Fig. 3. (a) sap flow meter installed on the main trunk of the tree. (b) The location of thermistors within the SFM1 needle set. (c) sketch of a needle inside the main trunk.](image)

![Fig. 4. A subset showing the diurnal behavior of the water-uptake rate (L.h$^{-1}$) measured by sap flow meters between May 20th and 24th, 2020.](image)
3. Results

3.1. Water-uptake rate behavior

The diurnal and annual behavior of the water-uptake rate measured by SFMs in Plots 30 and 31 was assessed based on a full year of data. Fig. 4 presents an example for a subset of water-uptake records, illustrating the water-uptake variations throughout the day, with low rates at nighttime, a rapid increase around sunrise (reaching a maximum rate at approximately 0800 KSA local time) followed by a relatively stable rate throughout the day until 1900 (KSA local time), when an abrupt flow rate decrease occurred. The observed diurnal shape matches with those observed for irrigated olive orchards in southern Portugal and Australia (Nuber and Yunusa, 2003; Santos et al., 2007).

Analysis of 10-min water-uptake annual cycle shows that the highest values were reached between 9 and 18 h and the lowest values was during 0–6 h, and 21–24 h (Fig. 5). For instance, for plot 30, the 10-min water-uptake at 1300 increased from 0.2 to 1.6 L per hour (L.h⁻¹) between January and July/August and decreased towards autumn, where it reached 0.25 L.h⁻¹ in November. In contrast, at 0300 h the 10-min water-uptake is around 0.2 L.h⁻¹ throughout the entire year. The obtained annual trend of water-uptake measurements is consistent with that measured by SFM instruments mounted on olive trees (Olea europaea L.) in Sicily, Italy (Puig-Sirena et al., 2021). Importantly, the diurnal and annual variations in the sap flow rates reaffirms the importance of using water-uptake data recorded coincidently with the SAR data acquisition when exploring any potential correlation.

3.2. Impact of soil parameters on SAR backscatter

When analyzing the sensitivity of the SAR signal to vegetation parameters in irrigated plots, it is important to ensure that SAR backscatter variations depend on vegetation only and are not related to irrigation activities and soil properties (surface soil moisture and roughness). To determine whether the SAR backscatter data are influenced by underlying soil moisture variations (roughness remains unchanged) in the super high-density olive orchards, we examined the 10 cm soil moisture measured by the sensor installed in Plot 50. Fig. 6a presents the 2-year temporal evolution of the SAR backscatter in VV and VH polarization and the soil moisture at 10 cm depth measured coincidently with the SAR acquisition time (18:30 local time). As can be seen, the SAR backscatter and 10 cm soil moisture measurements do not co-vary: i.e., the SAR signal does not increase or decrease in response to increasing or decreasing soil moisture values. The lack of relationship is verified in Fig. 6b, which shows no correlation between SAR and 10 cm soil moisture measurements, indicating that the temporal variation observed in SAR backscatter is indeed related to the variation of canopy parameters rather than soil moisture.

3.3. Sensitivity of SAR data to water-uptake

In this section, the temporal behavior of SAR backscatter between January 2019 and December 2020 extracted separately for the 52 plots was analyzed. Later, the correlation between the SAR backscatter and water-uptake rate was explored using the available data of water-uptake rate measurements collected for 4 months (January-May 2019) in Plot 50 and for a full year (2020) in Plots 30 and 31. The water-uptake rates recorded at SAR acquisition time (1830 KSA local time) were used to explore the correlation between SAR backscatter and water-uptake rate, as the latter show a diurnal variation (Figs. 4 and 5).

Fig. 7 shows the temporal evolution of SAR backscatter extracted separately for each plot. For the 52 plots that were studied, the SAR backscatter behavior has a general Gaussian shape, with backscatter increasing between January and mid-year (July/August), before returning to a minimum at the end of the year. The temporally increasing and decreasing behaviors of the SAR backscatter was higher in 2019 (up to 4 dB) than in 2020 (up to 3 dB) (Fig. 7). Importantly, the temporal increase and decrease were greater than the radiometric accuracy of Sentinel-1 (0.7 dB (El Hajj et al., 2016; Schwerdt et al., 2017)), revealing that the variation in SAR backscatter is related to variation in canopy parameters (Cermák et al., 2007; Way et al., 1990). There was no observed increase in the SAR backscatter that could be related to the appearance of new scattering elements (such as buds, flowers and fruit) resulting from phenological stages (El Hajj et al., 2014; Inoue et al., 2002; Lopez-Sanchez et al., 2011). This may be due to the type of olive trees studied, which has an evergreen canopy with elements smaller than the wavelength of the Sentinel-1 C-band (5.6 cm) (Rosenqvist and Killough, 2018). For instance, Inoue et al. (2002) showed that, unlike the C-band, the X-band can be used to detect the heading phase of rice because the heads are larger than the wavelength of the X-band. As the rice continues to emerge (LAI between 1 and 4), the X-band backscatter decreases due to attenuation, and then at the heading phase, the X-band

![Fig. 5](image-url)

**Fig. 5.** The annual cycle of the water-uptake rate (L.h⁻¹) of olive trees in Al-Jawf, Saudi Arabia, collected between Jan 1 – Dec 31, 2020. Each curve represents the averaged water-uptake rate over a 3-hour interval.
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backscatter begins to increase due to the enhanced backscatter from the rice heads. This behavior was not observed in the C-band SAR backscatter.

In theory, surface backscattering (VV polarization) increases as both the attenuation and signal depolarization decreases. Thus, the increasing backscatter in VV polarization between January and July/August suggests that the scattering originates mainly from the upper regions of the canopy, as attenuation and depolarization are significant when the transmitted wave penetrates deep into the canopy and interacts with the canopy vertical elements. In contrast, the volume scattering (VH polarization) increases when depolarization dominates the attenuation, meaning that the increasing backscatter between January and July/August is mainly caused by the interaction with vertically oriented canopy elements (i.e., the canopy volume). Moreover, the increases and decreases of the SAR signal (VV and VH) are enhanced by the increase and decrease of canopy moisture (Magagi et al., 2002; Pulliainen et al., 2004; Rao et al., 2020), respectively.

Since the SAR backscatter at all polarizations and wavelengths is related to the dielectric constant of the canopy (Magagi et al., 2002; Pulliainen et al., 2004; Rao et al., 2020), and the C-band backscatter is mainly from the tree canopy (top parts of canopy for VV and canopy structure for VH) due to limited penetration depth of the C-band, it is reasonable to assume that the increasing and decreasing backscatter (Fig. 7) is driven predominantly by canopy water content variations throughout the year (Magagi et al., 2002; McDonald et al., 1990; Pulliainen et al., 2004; Rao et al., 2020). Indeed, the water content of olive trees reaches a maximum in July/August. In September-October, the trees are subjected to water stress via reduced irrigation, which is a practice adopted by the farmers at the study site before harvesting to improve olive quality and facilitate mechanical harvesting. A similar observation was reported by Tubeileh et al. (2009) for olive trees in Syria as well as Bustan et al. (2016), who reported that olive tree water consumption for growth reaches its maximum during the summer period. It is worth noting that olive tree foliage volume does not change significantly during the year: excepting mechanical pruning around January. As such, SAR backscatter should not be unduly affected by volume variation given the managed state of these orchards.

Fig. 8 shows the temporal evolution of SAR backscatter and water-uptake at 18:30 for Plots 30, 31 and 50. Unfortunately, SFMs installed in Plot 50 were only operational for 4 months in 2019. During this time, a similar temporal evolution was observed for both SAR backscatter and the water-uptake rate at 18:30 for Plots 30, 31 and 50, with increasing behavior between January and mid-year (July/August), before returning to a minimum at the end of the year (Fig. 8). Fig. 9 presents the correlation between the water-uptake rate and the SAR backscatter data, with all data collected coincidentally at 18:30 (i.e. timed with the satellite overpass). As mentioned in Section 3.1, it is important to use coincident data due to observed diurnal variations in the water-uptake records. As shown in Fig. 9, both the original and smoothed SAR backscatter data display similar correlation slopes and intercepts based on the respective polarization. The original SAR backscatter data yielded an $R^2$ of 0.69 and 0.53 for the VV and VH polarizations, respectively, while the smoothed curves removed fluctuations (possibly caused by management practices or data noise

![Fig. 6](image_url)

(a) Temporal evolution of SAR backscatter (VV and VH polarizations) in Plot 50 and surface soil moisture at 10 cm depth (SM10) at SAR acquisition time. (b) Correlation between SAR backscatter (VV and VH polarizations) and SM10 at SAR acquisition time.

![Fig. 7](image_url)

Fig. 7. Temporal behavior of VV- and VH-polarized SAR data for all plots. A box plot is used to represent all backscatter values at a given SAR collection date (6 days revisit time). The boxes cover the backscattering values from the first quartile (Q1) to third quartile (Q3), with the line through each box, displaying the median value. The whiskers show the limits of Q1-1.5(IQR) and Q3 + 1.5(IQR) and circles indicate outliers.

![Fig. 8](image_url)

Fig. 8 shows the temporal evolution of SAR backscatter and water-uptake at 18:30 for Plots 30, 31 and 50. Unfortunately, SFMs installed in Plot 50 were only operational for 4 months in 2019. During this time, a similar temporal evolution was observed for both SAR backscatter and the water-uptake rate at 18:30 for Plots 30, 31 and 50, with increasing behavior between January and mid-year (July/August), before returning to a minimum at the end of the year (Fig. 8). Fig. 9 presents the correlation between the water-uptake rate and the SAR backscatter data, with all data collected coincidentally at 18:30 (i.e. timed with the satellite overpass). As mentioned in Section 3.1, it is important to use coincident data due to observed diurnal variations in the water-uptake records. As shown in Fig. 9, both the original and smoothed SAR backscatter data display similar correlation slopes and intercepts based on the respective polarization. The original SAR backscatter data yielded an $R^2$ of 0.69 and 0.53 for the VV and VH polarizations, respectively, while the smoothed curves removed fluctuations (possibly caused by management practices or data noise
and produced an $R^2$ of 0.81 and 0.75 for the VV and VH polarizations, respectively. In both cases, the line of best fits covers a dynamic range of 2.5 dB. The correlation observed in Fig. 9 is in agreement with the study of Way et al. (1990) and Heiska and Hallikainen (1994), who observed a variation in microwave backscatter that coincides with the dynamics of water-uptake variations for walnut and pine orchards. Finally, results showed that VV and VH behave similarly and both are well correlated to the water-uptake rate (Fig. 9). VV represents scattering from the canopy surface and VH relates to the volume scattering, as it represents the depolarized signal resulting from the interaction of the emitted wave with the canopy vertical elements (i.e. volume) (Lopez-Sanchez et al., 2013; Veloso et al., 2017). As SAR backscatter in VH polarization was correlated with the water-uptake rate measured during the whole year, it seems that the canopy volume does not change significantly enough to have an enhanced contribution to the SAR backscatter.

The above results infer that SAR backscatter is driven by the water-uptake rate and that the dynamics were larger in 2019 than in 2020 (Figs. 7, 8 and 9). As the water-uptake rate depends largely on the moisture content in the root zone, the difference in the dynamics of the SAR data behavior may be explained by water availability. To validate this, soil moisture (SM) data recorded by two soil moisture sensors installed in Plot 50 during 2019 and 2020 were used. Plot 50 exhibited higher SAR backscatter dynamics in 2019 (~4 dB) than in 2020 (~2 dB).
...depths (SM10 and SM30) suggest that Plot 50 received more frequent irrigation practices (quantity and frequency) in 2019 than in 2020 (Fig. 10). For example, assuming an increase in SM10 of more than 0.1 cm$^3$cm$^{-3}$ between two consecutive records represents an irrigation event, Plot 50 then had 86 irrigation events in 2019 compared to 41 in 2020 for the pre-August period, with irrigation starting earlier in 2019 (February) than in 2020 (April) (Fig. 10b). Therefore, the difference in SAR dynamics is consistent with irrigation practices (quantity and frequency) i.e. the more irrigation, the higher the water-uptake rate and, therefore, the higher the SAR data dynamics.

4. Discussion

The potential of Sentinel-1 SAR data to assess water-uptake in olive orchards was evaluated by comparing SAR data collected at a high incidence angle (42°) with in situ measurements of water-uptake inferred via sap flow rates. The sensitivity of the C-band SAR backscatter to canopy moisture provided the basis for exploring a relationship between SAR data and the water-uptake rate. The study also relied on numerous other investigations indicating that diurnal variation in microwave backscatter may originate from water movement in plants due to transpiration (Brisco et al., 1990; McDonald et al., 1990; Steele-Dunne et al., 2017; van Emmerik et al., 2015; Way et al., 1990). To date, no focused exploration has explored the potential of Sentinel-1 SAR data to assess the water-uptake rate in olive orchards. The use of SAR data as an irrigation management tool has so far focused on detecting irrigated areas in cropland instead of assessing physical variables such as water-uptake guide irrigation application (Bazzi et al., 2019; Gao et al., 2018; Ma et al., 2022). More generally, the use of SAR data to explore the biophysical parameters of orchards is an emerging topic of research.

No correlation was observed between the SAR backscatter acquired from super high-density olive orchards (1 tree per 6 m$^2$) and the measured soil moisture. This either indicates that the C-band SAR signal at a high incidence angle does not penetrate the tree canopy (i.e. does not reach the soil), or that only the soil moisture around the tree trunk changes (due to the specific locations of drippers for irrigation) while the inter-row soil moisture remains dry, resulting in only slight changes in the overall soil moisture status of the plot. Nevertheless, the lack of correlation between SAR backscatter and soil moisture ensures that the SAR backscatter can be more confidently related to the characteristics of the olive trees.

The results showed that the temporal behavior of the SAR backscatter (collected around 1830 local time) from all of the investigated olive plots presented a Gaussian response (Fig. 7), with increasing backscatter between January to July/August, and subsequent decreasing backscatter towards the end of the year. The increasing and decreasing behavior of the backscatter was higher than the SAR radiometric accuracy, indicating that the variation is driven by the canopy dielectric constant. Indeed, this behavior was found to correspond well to the temporal response of the water-uptake rate as measured via the sap flow meters at the time of SAR acquisition (1830), resulting in an $R^2$ of 0.81 (Fig. 9). These results are consistent with diurnal variation observed by a C-band scatterometer over a walnut orchard, where the backscatter increased about 2 dB between midnight (no water-uptake) and the afternoon (high water-uptake) (Way et al., 1990). Accordingly, the water-uptake rate determines how much water passes from the soil to the plant and then to the atmosphere at a given time, resulting in a correlation between SAR backscatter and water-uptake measured coincidently with SAR data acquisition.

In addition, results also showed that increasing SAR backscatter between January and July/August is higher in 2019 than in 2020, which was found to align with higher irrigation frequency in 2019 in comparison to 2020. This supports the significance of the correlation between SAR backscatter and sap flow obtained in Fig. 9, demonstrating that the SAR data provide a potential means to assess the water-uptake rate and irrigation applied. To generalize our findings for olive orchards, the potential of SAR data to assess the water-uptake rate must be further explored for olive orchards located in other regions with different climatic conditions.

Water-uptake is a key factor that determines canopy water content and biomass (Nuberg and Yunusa, 2003). Many studies have reported a correlation between SAR backscatter and water content and biomass (Magagi et al., 2002; Paget et al., 2016; Pulliainen et al., 2004; Rao et al.,...
Unfortunately, information on canopy water content and biomass was not available and thus it was not possible to explore which of these parameters (water uptake, canopy water content, and biomass) had the highest correlation with SAR backscatter. However, the results show that the C-band SAR backscatter of the studied olive orchards could not accurately estimate the biomass, at least without considering the change in water status (water uptake and water content) (Khabbazan et al., 2022). Indeed, SAR backscatter shows temporal variation during a period when the canopy is not changing (i.e. early stage and after harvest in September).

In this study, SAR backscatter do not show a particular response to any of the phenological stages. Several studies have shown the potential of SAR data for estimating key phenological stages of crops (wheat and rice) using abrupt changes in backscatter as an indicator of the appearance of new elements (such as panicle and fruit) in the canopy (El Hajj et al., 2014; Lopez-Sanchez et al., 2011). The lack of abrupt changes in backscatter of the olive orchards can be explained by the fact that the C-band wavelength is larger than the dimension of elements of olive trees and thus is not sensitive to their appearance (flowering, buds, and fruit) throughout the year (Rosemynt and Killough, 2018). The use of SAR data with smaller wavelength such as X-band (~3 cm) data may facilitate the estimation of key phenological stages.

In this study, the experiment was performed on orchards with mechanically harvested and pruned olive trees of homogenous dimensions and density. As SAR backscatter depends on vegetation vertical structure (Macelloni et al., 2001), the results obtained herein are specific to the assessed olive orchards. A possible operational solution to eliminate the effect of canopy morphology and generalize an approach to assess the water-uptake rate could be to assess the difference in backscatter between two SAR images acquired early in the morning (low water-uptake rate) and late afternoon (high water-uptake rate) on the same date. Unfortunately, the availability of Sentinel-1 data over the study site did not allow this approach to be tested. Further research should explore other orchards with different tree planting densities and species to assess their impact on the correlation between water-uptake and SAR backscatter. Based on previous research, a correlation between SAR backscatter and water-uptake for other orchard types is expected due to reported relationships between SAR backscatter and water movement in plants (Heiska and Hallikainen, 1994; McDonald et al., 1990; Steele-Dunne et al., 2017; Way et al., 1990).

5. Conclusion

The capacity to use Sentinel-1 SAR backscatter for monitoring water-uptake of olive trees was explored. The results showed that the SAR backscatter of olive tree plots increases from January through to July/August, and subsequently decreases for the remainder of the year, following a Gaussian response. The SAR backscatter dynamics were found to be well correlated with in situ sap flow rates measured in three plots, providing insight into tree water-uptake. To reduce the potential effects of canopy structure on SAR backscatter, the correlation between SAR backscatter and water-uptake rate was explored using data acquired over three olive plots having similar conditions (tree type and planting density). Therefore, the correlation between SAR backscatter and the water-uptake rate reported herein is specific to olive orchards within the study area. Future work should use denser in situ records to assess how olive tree orchards of different tree densities, age groups, and management practices affect SAR backscatters in relation to water-uptake. Overall, the study demonstrated the potential of SAR data acquired at high resolution and high revisit time to monitor water-uptake rate in olive orchards and paves the way to investigate the accuracy of SAR derived water-uptake. SAR derived water-uptake with suitable accuracy would prove insights that could enhance crop-water use models and offer a useful tool for improved irrigation and crop management.

References


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