

The synergy of optical data with microwave backscattering model for the retrieval of soil and vegetation conditions in heterogeneous Mediterranean environment

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ABSTRACT

Estimation of soil moisture and vegetation biomass over wide regions is needed for a better understanding of ecological conditions and for monitoring desertification processes in fragile environments such as the Mediterranean region. Satellite remote sensing, with appropriate processing, could be very well suited for this task. In this work, we provide a multi-temporal analysis of backscatter characteristics of four major vegetation formations in Mediterranean regions. This analysis together with a description of the relationship between volumetric soil moisture and ERS-2 SAR data from Mediterranean soils enabled us to adapt the water-cloud model of Attema and Ulaby (1978) to Mediterranean vegetation canopies. The application of the adapted model in heterogeneous plots was possible by the use of vegetation formation pixel fractions from Landsat TM data. The results have shown considerably good agreement between predicted and measured green biomass in both homogenous and heterogeneous plots.

1 INTRODUCTION

Regions with Mediterranean climate are being located in transition zones between humid and arid climates. In the Mediterranean basin these climatic conditions, together with the long and intensive use of the land, have resulted in complex environments. A better understanding of ecological processes in this sensitive zone and more effective landuse management require detailed quantitative information of vegetation and soil properties over wide regions. Radar remote sensing from satellites is very well suited to this task. However, currently, modeling vegetation with radar data is mainly being utilized for spatially homogenous vegetation layers such as: agricultural crops; forests; and wide grasslands and it is very limited for applications in heterogeneous areas such as exist in the Mediterranean region. This report contributes to increase the knowledge of using SAR data in a Mediterranean region. The objectives of this study are: (i) to generalize a soil moisture model for various soils along a semi-humid to semi-arid climatic gradient; (ii) to adapt a backscatter semi-empirical model to the conditions of the study area as representative to the Mediterranean region; (iii) to invert the adapted model in order to derive herbaceous vegetation green biomass estimations from the ERS-2 SAR backscatter.

2 DATA

The study area is a semi-arid phyto-geographical zone along a rainfall gradient with annual average between 450 mm and 250 mm, located in the central of Israel along the eastern coast of the Mediterranean basin. The dominant rock formation is chalk with patches of Calcrete and the dominant soil is Brown Rendzina (Haploxerolls). Vegetation in this area varies from shrublands and garigue (dominated by *Quercus calliprinos* and *Phillyrea latifolia*), through dwarf shrubs (dominated by *Sarcopoterium spinosum*) to open areas with diverse grasslands vegetation (dominated by *Gramineae*). The spatial patterns represent wide range of transitional stages between areas of high homogeneity of mainly tall shrubs and grasslands with different compositions of the three vegetation formations. This diversity of patterns is a result of a long history of human activity (since the late bronze, approximately 5500 years ago). At the present, land use in this area is composed of agricultural crops and rangelands with controlled grazing pressures. The study area is characterized by wide range of "regeneration and degradation patterns" of patches representing various soil-vegetation relationships, which may allow generalization of the methods to wider areas of transition between Mediterranean and arid regions.

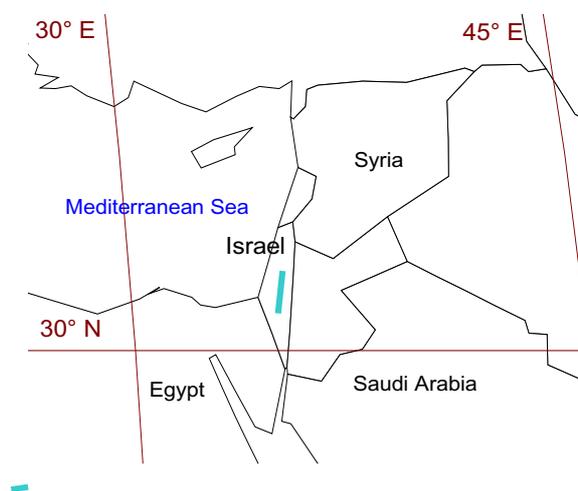


Figure 1. The study area within a regional context.

Two specific study sites were selected to represent the extreme conditions of the climatic gradient in the study area: Avisur site representing the northern and humid zone and Lehavim site representing the more southern and arid zone. The remote sensing data used in this study include three ERS-2.SAR.PRI C-band images, acquired at February, April and May 1997. These dates represent the vegetation status in the study area at the beginning, peak, and the end of the winter season and thus provide a variety of phenological phases of annual herbaceous vegetation. In addition to the remote sensing data, a detailed field campaign was carried out simultaneously with the satellite overpass. Measurements of gravimetric soil moisture (at the top 5 cm) using the double weight technique were taken and herbaceous vegetation green biomass, was measured randomly along 100 meter transects using the harvest and assessment method (Tadmor *et al.* 1975).

3 METHODS

The remote sensing methodology proposed here includes a calibration of the ERS-2.SAR.PRI image DN to sigma naught (decibels and power units) considering both viewing geometry and local topography. In addition, correction of the image's file coordinates to Real World coordinates (Israel New Grid) was carried out based on 250 ground control points and a first order algorithm with a root mean square error of less than one pixel. The derivation of backscatter (σ^0) from the DN value of ERS-2 SAR PRI image (equation 1) was executed based on the method of Laur *et al.* (1997):

$$\sigma^0 = \left[\frac{1}{N} \sum_{ij=1}^{ij=N} DN_{ij} \right] \frac{1}{k} C \left(\frac{\sin \alpha}{\sin \alpha_{ref}} \right) \quad (1)$$

where N is the number of pixels within an area of interest; DN is the ERS-2 SAR image digital number and the average in the square parenthesis is calculated following the application of a mean filter with a 3x3 pixel window size to reduce speckle effects; K is the processing center specific calibration constant; C accounts for updating the gain due to the elevation antenna pattern implemented in the processing of the ERS SAR PRI data products and α , and α_{ref} are the mid-range and reference incidence angle respectively. Since the study area is hilly, backscatter was adjusted for variations in the local angle of incidence, derived from a digital elevation model (Shoshany *et al.* 1998).

The image preprocessing enabled to derive ERS-2 SAR backscattering coefficient values from surface covered by the four dominant Mediterranean vegetation formations. The image sampling procedure was executed at 50, relatively homogenous, plots per vegetation formation per date. The understanding of the backscattering mechanism from the Mediterranean vegetation formations has lead us to apply the semi-empirical water cloud model (Attema and Ulaby 1978). This model was applied earlier for vegetated surfaces based on ERS-2 SAR data but was mainly used for agricultural crops (Xu *et al.* 1996). The general form of the water cloud model is described in equation 2:

$$\sigma^0 = Af(L)\cos \theta(1-\exp(-2BL/\cos \theta))+(C+ Dm_s)\exp(-2BL/\cos \theta) \quad (2)$$

where σ^0 is the radar backscatter [m^2/m^2]; $\cos \theta$ is the cosine of the incidence angle; L is a canopy descriptor such as LAI or biomass; and $(C+Dm_s)$ is the soil contribution which can be derived from the linear soil moisture model and converted to power units [m^2/m^2]; A and B are the canopy coefficients and should be adapted empirically to each vegetation layer. The determination of the canopy coefficients was executed by a non-linear least square regression code based on the E04FDF procedure of the NAG libraries. The initial points were set to 0.005 for both coefficients based on previous works that determined the canopy coefficients for agricultural crops such as wheat (Prevot *et al.* 1993) and sugar beet (Xu *et al.* 1996).

This form of the water cloud model could be used for homogenous areas but is not suitable for the heterogeneous environment that characterize the Mediterranean region. In order to adapt the water-cloud model for Mediterranean environments we propose to include in the model the unmixing method of Shoshany and Svoray (2000) which is based on a multi-temporal multi-spectral approach. This adaptation has enabled us to receive the contribution of each of the vegetation formations to each pixel. Our suggestion for the application of the water-cloud model in heterogeneous areas is to incorporate the cover fraction assessments applied on Landsat TM images with the general form of the water cloud model. Such a an incorporated model can use the form described in equation 3:

$$\sigma^0 = A_s f_s \cos \theta (1 - \exp(-2B_s GVD_s / \cos \theta)) + A_d f_d \cos \theta (1 - \exp(-2B_d GVD_d / \cos \theta)) + A_h f_h \cos \theta (1 - \exp(-2B_h GVD_h / \cos \theta)) + f_h (C + Dm_s) \exp(-2B_h GVD_h / \cos \theta) \quad (3)$$

where different A and B canopy coefficients are related to the different three vegetation formations – shrubs, dwarf shrubs and herbaceous vegetation; different f are the cover fractions of the three vegetation formations and different

GVD are the green leaf volumetric densities of the three vegetation formations as formulated in the study of Svoray et al. (2000). The use of the green leaf biomass volumetric density rather than the green leaf absolute biomass provides a better representation of the backscatter contributors in the different vegetation canopies. Green leaf biomass [kg m^{-2}] values of the GVD were received from the above mentioned field campaign. The soil moisture coefficients and the local incidence angle were considered as described in the general form of the water cloud model. The mixed proposed model can be more clearly illustrated and explained using figure 2.

The difficulties involved with modeling the backscatter from a mixed pixel of herbaceous and woody formations are mainly related to different scattering mechanisms of the two canopies. Due to the low penetration depth at C-band, the interaction of the radar beam with the surface includes the soil moisture effect in the case of herbaceous vegetation but involves only the uppermost layer of the canopy in the case of the woody formations. Thus, contribution of soil moisture to backscatter of a mixed pixel is only from the parts of the pixel that are covered with herbaceous vegetation. The other parts of the pixel, covered with woody formations, contribute only from the upper part of the canopy. The solution provided by us is to include the soil contribution only in the areas covered by the herbaceous vegetation.

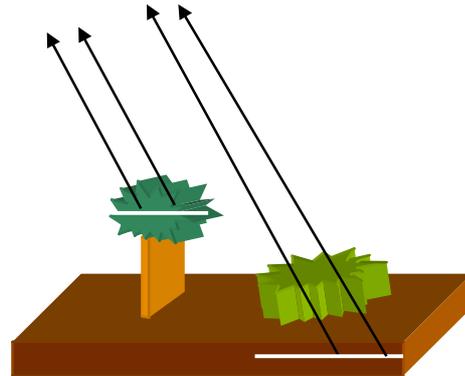


Figure 2. An Illustration of backscatter from a mixed pixel.

4 RESULTS AND DISCUSSION

This section describes the linear relationship that were found between ERS-2 SAR backscatter and volumetric soil moisture in the study area; multi-temporal ERS-2 SAR backscatter curves of the dominant vegetation formations in the study area; and finally results of applying the water cloud model in homogenous and heterogeneous plots are discussed and the predicted values of the inversion models are being assessed.

Examination of the relationship between volumetric soil moisture and ERS-2 SAR backscatter have shown a strong linear correlation between volumetric soil moisture and ERS-2 SAR backscatter. Statistical tests have proven ($\alpha=0.05$) that this relationship did not vary along the climatic gradient. This similarity between the linear soil moisture models of a humid and arid sites and other models that were applied to different environments around the world, have lead us to conclude that a unified model (figure 3) could be applied for the entire climatic gradient region.

The results in the unified model illustrate high level of scattering in points at the lowest levels of volumetric soil moisture (between 0% to 10%) and at the highest levels of moisture (between 25% to 40%). The points in between these ranges are characterized by much more closeness to the regression line. This result may imply on the sensitivity of the ERS-2 SAR backscatter and the linear soil moisture model to changes in the soil moisture concentrations. Thus, although the results in the upper and lower parts of the plot are reasonable and the total coefficient of determination is high (0.9), it appears that the best range to be represented by the soil moisture model is the between 10% to 25% of volumetric soil moisture concentration. This range, although is relatively short, is very meaningful for the analysis of water stress in semi-arid areas.

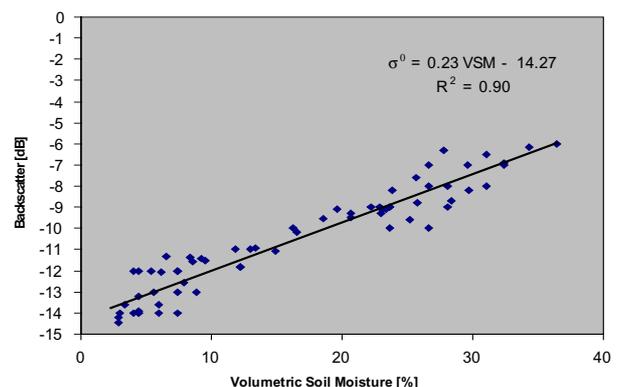


Figure 3. The relationship between the ERS-2 SAR backscatter and the volumetric soil moisture along the climatic gradient.

A study of ERS-2 SAR backscatter from canopies of the dominant vegetation formations in the study area (trees, shrubs, dwarf shrubs and herbaceous vegetation) prove a clear difference between the multi-temporal curves of backscatter from woody formations (trees, shrubs and dwarf shrubs) and the multi-temporal curves of herbaceous vegetation (grasses and wheat) canopies. In general, the woody formations provide relatively stable multi-temporal

curves and the herbaceous formations present changes in backscatter along the growing season. Figure 4 is illustrating the variations in backscatter from annual vegetation canopies at February, April and May 1997.

Figure 4 shows that the mean backscatter from herbaceous vegetation and crops is very similar at February and May. On the contrary, a significant difference ($\alpha=0.05$) was found between the backscatter from the canopies of these two formations at April. Moreover, figure 4 shows that the backscatter from the two formations in February is similar to the backscatter from the two formations in May and the backscatter at these two months differs significantly from the backscatter at April. This two observations which to our assessment are related to the same cause may have the following explanation: on February when the natural herbaceous vegetation and crops (wheat) are still low, and on May when the herbaceous vegetation is withered and the wheat is harvested, a relatively high backscatter is recorded in the ERS-2 SAR antenna. This may occur due to the strong effect of soil at these two phenological phases of the annuals. On April when the herbaceous vegetation is grown, it presents a high level of biomass and the contribution of lower constituents (soil moisture and soil roughness) is masked and thus the mean backscattering values are relatively low. This result may imply that the contribution of the soil to the total backscatter is much stronger than the contribution of the vegetation canopy. Thus in April when the effect of the vegetation prevails, the backscatter from the different canopies differs, but when the soil contribution prevails the soil underneath the two formations presents similar backscatter. This phenomenon has a strong influence on radar modeling of annuals and it should be considered when trying to determine quantitative biophysical attributes of from variations in backscatter. On the contrary to the case of the herbaceous vegetation, the ERS-2 SAR backscatter, recorded from homogenous plots of woody vegetation formations (forests, shrublands and dwarf shrublands) appeared as relatively stable along the growing season.

Thus the backscattering from these formations did not vary significantly ($\alpha=0.05$) between the three dates of observation. This result is very well illustrated in figure 5. The backscattering curves of shrubs and dwarf shrubs are very similar and the curve of the trees keeps the same trend but with much higher values of backscatter. The reason for this may be the much more dense layer of the trees at the upper part of the canopy than the upper part layer of the lower formations. This result is in line with an earlier observation of Quegan et al (1998) who measured the multi-temporal backscatter from the King's forest in the U. K. their results indicate that mature pine trees perform a relatively stable (between -8 and -12.5) backscatter curve between January and December 1997. The explanation for the stability of the backscatter from the woody formations along the vegetative season may be the relative stability of the moisture content in the canopies of these formations along the year, especially when it is in comparison to the water content in the herbaceous vegetation.

The observation of the strong effect of soil moisture on the herbaceous vegetation but not on the woody formations have lead us to the understanding that a combined model should be developed and include the following rule: the areas covered by the herbaceous vegetation should include the contribution of soil moisture and the areas covered by woody formations should include only the effect of the upper part of the canopy. The difference between the trees and shrubs / dwarf shrubs may imply on the effect of leaf density at the upper part of the canopy layer on backscatter. At the first stage, the water cloud model was applied to areas of homogenous herbaceous vegetation cover. The use of an inversion model enabled to predict herbaceous vegetation biomass from the ERS-2 SAR backscatter. Comparison of measured and predicted herbaceous green biomass is illustrated in figure 6.

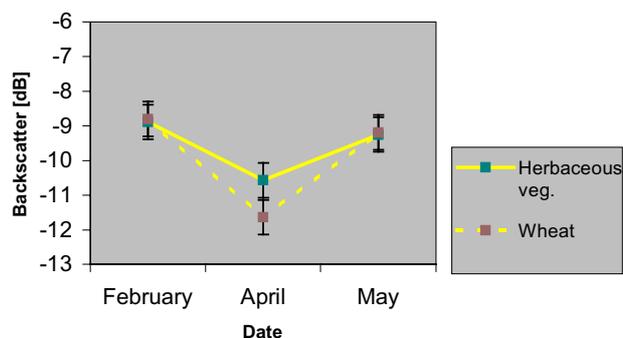


Figure 4. The relationship between the ERS-2 SAR backscatter and plots of natural herbaceous vegetation and crops. The points represent mean values and confidence intervals ($\alpha=0.05$) of 50 points to each of the formations per date.

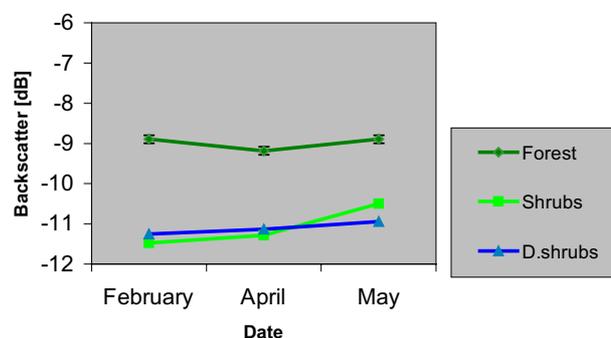


Figure 5. The ERS-2 SAR backscatter from plots of woody formations. The points represent mean values of 50 points to each of the formations per date.

Coefficient of determination of 0.9 has been achieved for points representing eight relatively homogenous plots of herbaceous vegetation. When considering the complex conditions of the study area, this level of accuracy is satisfactory. However it is important to note that in two cases the predicted biomass values have suffered considerably high overestimation. The two points were examined carefully but we could not find any particular environmental condition, which may explain their abnormality. This observation will be more closely examined with a larger database. If the analysis of a larger database will show the same trend, the overestimation could be normalized with an empirical factor. The case of heterogeneous plots was much more complex, involved more factors and thus yields less strong relationship (coefficient of determination of 0.79). The case of heterogeneous plots differs from the case of homogenous plots in two major aspects: first, the range of herbaceous vegetation green biomass in the case of the heterogeneous plots is much more limited obviously as other vegetation formations exist in plots; and secondly, there is lack of consistency in overestimation in the case of heterogeneous plots: over and under estimations seem to be more or less equal. To summarize this part we may say that it is well believed that albeit the reduction in the significance of the relationship between the herbaceous green biomass and ERS-2 SAR backscatter in the case of heterogeneous plots, it is still a promising result which may be well improved with the determination of more precise coefficients with increasing the database and more attempts to determine best initial points.

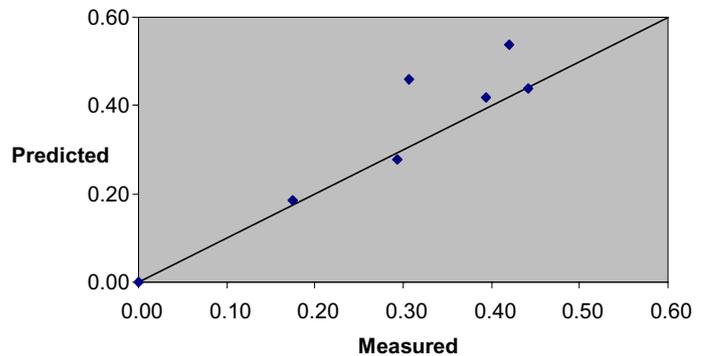


Figure 6. The relationship between predicted and measured herbaceous vegetation green biomass [Kg m⁻²] in homogenous plots.

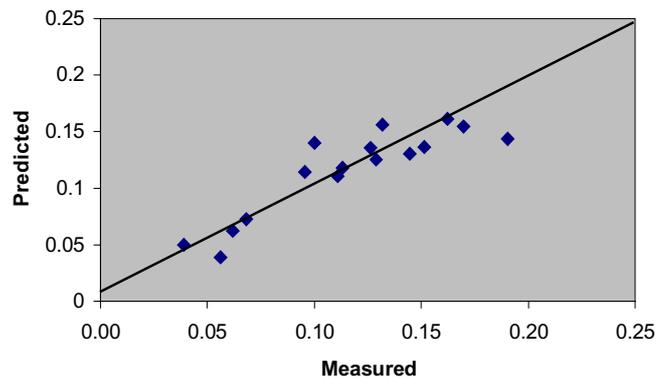


Figure 7. The relationship between predicted and measured herbaceous vegetation green biomass [Kg m⁻²] in heterogeneous plots.

5 SUMMARY AND CONCLUSIONS

Multi-temporal characteristics of the ERS-2 SAR backscatter from four Mediterranean vegetation formations were studied in the semi-arid zone of Israel. Significant differences were found between the multi-temporal backscatter signatures of herbaceous vegetation and woody plant formations. The application of semi-empirical backscatter model in conjunction with cover fractions derived from Landsat TM data enable to adapt successfully the water-cloud model to the Mediterranean environment. Significant correlation was observed between the predicted and estimated values of herbaceous green biomass in homogenous and heterogeneous (mixed) plots. These results imply on the potential of the ERS-2 SAR data for the estimation of herbaceous vegetation green biomass in wide regions.

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