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ASSESSING THE EFFECTIVENESS OF LAND RESTORATION INTERVENTIONS IN DRY LANDS BY MULTITEMPORAL REMOTE SENSING – A CASE STUDY IN OULED DLIM (MARRAKECH, MOROCCO)

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ABSTRACT

Atriplex nummularia has been extensively planted in Northern Africa to combat desertification. However, few studies evaluated the effectiveness of these interventions. This study aimed at assessing the dynamic performance of a number of Atriplex plantations located in the Marrakech province in terms of multitemporal dry biomass production. Three SPOT 5 images (2004, 2008 and 2012) and field biomass measurements were integrated to quantify the dry biomass production dynamics of plantations established from 1996 to 2007. Different plant ages covered the whole plant life cycle curve. Vegetation indices were derived from the images and those of 2012 were coupled to the measured biomass of 2012 to formulate biomass models. An analysis of shrub biomass production was conducted in plantations and in adjacent rangelands, covering varying degree of plant development, and an estimate of the economic benefits generated by the plantations in terms of available fodder biomass was performed. The results show that, on average, the plantation sites produced 2·21 to 3·61 $Mg\,ha^{-1}$ of dry biomass more than the surrounding rangelands. The best performing plantations yielded even greater differences, up to more than 7 $Mg\,ha^{-1}$. It was observed that the most performing plantations, while contributing to mitigating land degradation, have generated economic value and could compensate the economic cost of the intervention even under drought conditions. However, in several cases the plantation performance was far from sustainability, particularly due to poor management (early and/or over grazing), revealing that management is a critical factor for the success of this restoration practice. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS: desertification; *Atriplex*; biomass; vegetation indices; rangeland; rehabilitation; assessment; monitoring

INTRODUCTION

Desertification, as a consequence of both natural and human activity, is the major threat and challenge for human societies in arid and semiarid regions (UNCCD, 1994). Desertification is a complex issue, taking on different forms and processes in different ecosystems (Warren, 2002; D'Odorico *et al*., 2013). Its direct causes can be mainly ascribed to land mismanagement, such as overgrazing, deforestation, inappropriate use of irrigation and non-conservative agriculture practices (Thomas & Middleton, 1994; Geist & Lambin, 2004; Geist, 2005), which are driven by underlying forces, such as policy implementation, demand of national and international markets and poverty (Geist & Lambin, 2004). Desertification and land degradation can take place in different climatic regions of the world (Izzo *et al*., 2013; Symeonakis *et al*., 2014; Wang *et al*., 2013). Desertification is particularly contributing to the depletion of soil resources in arid and semiarid rangelands, increasingly threatened by population growth and overexploitation (Cerdà & Lavee, 1999; Reynolds & Stafford Smith, 2002; Bedunah & Angerer, 2012).

The actions to combat desertification and land degradation can be broadly classified as prevention, mitigation and restoration interventions (Zucca *et al*., 2013a). The restoration actions often involve the improvement of vegetation cover through, for example, the (re)introduction of adapted species, the control of invasive species and reforestation. Soil and water conservation are examples of prevention and mitigation and may include a range of approaches, among which improved soil management (Zhao *et al*., 2013; Mcdonagh *et al*., 2014). Many technical options are available to recover the productivity of the degraded rangelands, which are adapted to the different ecosystem conditions and local contexts (King & Hobbs, 2006; Kinyua *et al*., 2010). They include passive (grazing exclosure; Gökbulak & Hizal, 2013) and active strategies, such as managed and rotational grazing, control of shrub encroachment (Fulbright, 1996), vegetation reseeding (Wiedemann, 1987) and planting of fodder shrubs and trees (Le Houérou, 2000).

The development of analytical methods for evaluating the success of the actions to combat desertification is considered as crucial by the scientific community (Reynolds *et al*., 2007) and is actively promoted by the United Nations Convention to Combat Desertification. However, land degradation and restoration processes may produce complex and contrasting effects on the different ecosystem services involved, making desertification assessment a challenging exercise (Sommer *et al*., 2011; Zucca *et al*., 2012). Although an increasing number of scientific articles was devoted to

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this subject, particularly in dry rangeland areas (Mekuria & Aynekulu, 2011; Thomaz & Luiz, 2012; Kröpfl *et al.*, 2013; Roa-Fuentes *et al.*, 2013), few studies aimed at assessing the effectiveness of the interventions to combat desertification (De Pina Tavares *et al.*, 2014). The available assessments were in many cases carried out in a non-integrated way, for example, by neglecting the social and economic implications. Furthermore, they were often performed on a small plot scale, and large-scale monitoring was rarely performed.

To conduct the evaluation over a wider area or region, the spatial observation tool and remote sensing should be employed (Rango *et al.*, 2002) as satellites can macroscopically and periodically observe the rather large area or region of interest and obtain multitemporal and even time-series land surface information (Wu, 2009; Wu *et al.*, 2013a). Thanks to these advantages, remote sensing has been widely applied to land characterization in dry land systems, including land cover change detection, desertification monitoring, land degradation assessment and analysis of the impacts of land management policies. That was achieved by applying the thresholding and differencing and classification techniques on albedo (Courel *et al.*, 1984; Otterman & Tucker, 1985), or vegetation indices (Malo & Nicholson, 1990; Tucker *et al.*, 1991; Evans & Geerken, 2004; Wu, 2009; Wang *et al.*, 2013; Wu *et al.*, 2013b), taking the response of vegetation to rainfall into account or by spectral unmixing approach (Shoshany & Svoray, 2002; Hostert *et al.*, 2003). A number of studies have demonstrated the quantification of the photosynthetically active herbaceous and shrub biomass production in rangelands and savannahs either by the integrated spectral vegetation indices of the growing period (Tucker *et al.*, 1985; Wessels *et al.*, 2007) or by the annual peak or maximum vegetation indices (Tucker *et al.*, 1985; Wylie *et al.*, 1995; Bénié *et al.*, 2005; Wu & De Pauw, 2010; Wu *et al.*, 2013a, 2013b) through coupling/modelling procedure. However, few remote sensing studies have focused on assessing the effectiveness of human interventions, for example, restoration/recovery through land management. It is hence necessary to develop effective remote sensing-based approaches for such assessment in a wider area, which can be, theoretically, undertaken by tracking the change in albedo or greenness or change in biomass production. The latter is the direct indicator of land productivity and is thus more relevant than the other indicators for this purpose.

This research targeted a specific type of rangeland rehabilitation intervention (fodder shrub plantation) extensively carried out in Morocco to combat desertification. There, *Atriplex nummularia* L. (Amaranthaceae; Oldman saltbush) plantations were widely implemented in pilot sites, particularly in the Marrakech region since the 1990s. Such species, native to Australia, was introduced in the northern Mediterranean area because of its resistance to aridity and grazing, becoming the most important exotic shrub species utilized on a large scale to date in the Mediterranean Basin (Le Houérou, 1992). It is palatable for livestock and provides a high fodder production and green biomass for all-year grazing (Le Houérou, 1992).

The objective of this study was to develop a biomass-based remote sensing approach to assess the dynamic performance and the effectiveness of those restoration interventions. Multitemporal remote sensing data were obtained, and field measurements were conducted for an integrated analysis.

STUDY AREA AND METHODS

Study Area

The study was conducted in pilot sites located in the Rural Municipalities of Ouled Dlim and M'nabha (Marrakech region; Figure 1). The region is characterized by dry and hot summers spanning from May to October. The average annual precipitation was 202 mm in Ouled Dlim and 222 mm in Marrakech in the period 1983–2012. The annual potential evapotranspiration (PET) calculated based on the FAO Penman-Monteith method (Allen *et al.*, 1998) is about 1590–1820 mm in Marrakech. The aridity index (P/PET) is between 0·098 and 0·166 ('arid' according to UNEP, 1997).

The central part of the area is characterized by the Jebilet relieves, where schist constitute the main bedrock (Huvelin, 1970). Relieves are gently undulating. Soils are shallow and degraded because of overgrazing and subsistence cropping. Although cereal harvesting (rainfed barley and wheat) is carried out only in particularly rainy years, in some areas soil is ploughed almost every year for fodder production. Sparse individuals of *Ziziphus lotus* L (Rhamnaceae) and rare *Acacia horrida* L. (Mimosaceae), along with scattered shrub species typical of the degraded pasturelands, such as *Peganum harmala* L. (Nitrariaceae), constitute the perennial vegetation cover.

In the study area, *Atriplex* plantations were established along linear furrows made through a ripper. Plant density varies between around 1,000 and 700 plants per ha (with somewhat regular planting grids of, respectively, 3 m × 3 m or 4·5 m × 3 m). The intervention were mainly funded and carried out by the local administration with the participation of the local communities, which were stimulated to create cooperative organization to better manage the planted land. Typical plantation time is February–April. Plots are opened to grazing only at the end of summer of the third year, to protect the earliest plant development phase. During the following years, the users are recommended to implement controlled grazing strategies. However, because of poor enforcement and monitoring, grazing management may vary significantly across the different beneficiary communities.

Atriplex Biomass Sampling

Field sampling and measurement were conducted in 10 plantation sites on 21–29 March 2012. The *Atriplex* biomass of each site was determined in five plots including four to five plants (or less, in case of missing plants) belonging to two plantation lines, and covering a surface of 50-70 m^2, depending on the planting density. The five plots were regularly located in a 2500 m^2 area (Figure 1). Plant size was measured by determination of the plant height and of two orthogonal plant canopy maximum diameters (North-South

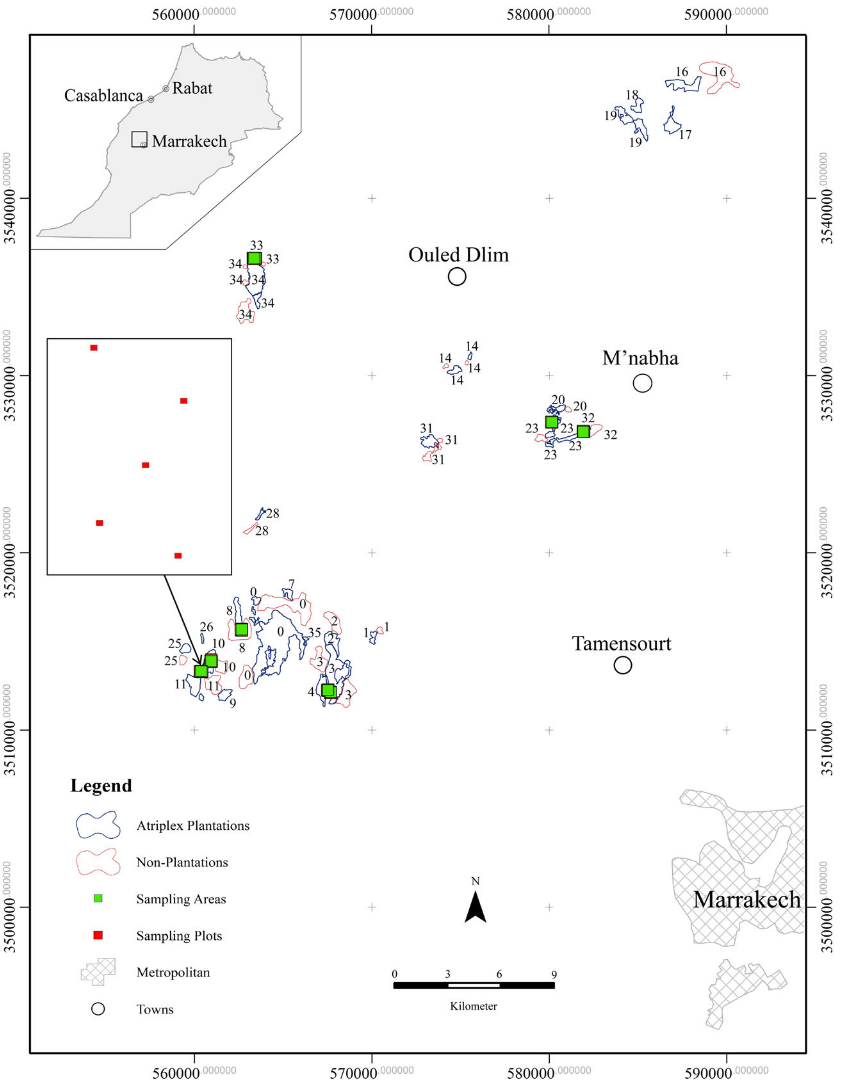

Figure 1. Location of the planted and non-planted reference sites (blue and red polygons with corresponding numbers) and of the biomass sampling areas (green squares). In each sampling area, five sampling plots were defined (red squares). Inset map: location of the study area. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

and East-West). In consideration of the variability of *A. nummularia*, a plant shape was assigned to the plants: elliptic, spherical or hemispheric. The canopy volume of the plants was calculated based on the recorded biometric data and to the assigned plant shape. One plant per plot was sampled for fresh and dry biomass weight determination. Data on fresh and dry biomass were used to calculate the mean quantity of biomass per plot area, according to a procedure described in detail by Zucca *et al.* (2013b). Overall, total fresh (wet) biomass (TFB; Mg ha^{-1}), total dry biomass (TDB; Mg ha^{-1}) and canopy cover (CC; %) were determined in 49 plots. The centre location and the average biomass of each plot were obtained and matched to the 10 m size pixels of SPOT images.

Planted and Non-Planted Polygons

Polygons were drawn by means of the ArcGIS software to delimitate relatively large and homogeneous plantations sites, both around the field plots and in additional plantations areas. In all cases, control polygons of similar size were drawn in the surrounding non-planted (control) rangeland areas (Figure 1). Care was taken in order to ensure the comparability between plantation and reference polygons in term of bedrock, landform and soils, based on previous studies (Zucca & Previtali, 2007; Zucca *et al*., 2011) and on the visual interpretation of the remote sensing data.

The herbaceous cover was estimated along 50-m long linear transects in both the planted and non-planted sites. The canopy cover of the woody wild shrubs (*Ziziphus lotus*) was visually estimated for the non-planted sites based on high resolution satellite images.

Satellite Imagery and Rainfall Data

Three multitemporal SPOT 5 images including both multi-spectral (10 m resolution) and panchromatic fused (sharpened) bundles (XS1, XS2 and XS3 with resolution of 2·5 m) dated 06 March 2004, 11 March 2008 and 27 February 2012 were obtained (Table S1). The period February–March represents the peak greenness of the herbaceous vegetation. Monthly rainfall data in the period 1983–2012 were obtained from the station of Ouled Dlim, in the study site, and daily and monthly data from the stations of Marrakech, Safi, Essaouira, Kasba-Tadla, Beni Mellal and Nouasseur in the surrounding region. Annual rainfall data for the Ouled Dlim station are shown in Figure 2.

Image Processing

Atmospheric correction

The numerical level (or digital number) of each band (XS) of all SPOT 5 images was first converted into at-satellite radiance (L_k) in line with the instruction of CNES (2012) by the following equation (Equation 1):

$$X_k = A_k G_{mk} L_k \text{ or } L_k = X_k / A_k G_{mk} \quad (1)$$

Where: L_k is at-satellite spectral radiance of band k (W m^{-2} sr^{-1} μm^{-1}), X_k is the numerical level (or digital number), A_k is the absolute calibration coefficient (W^{-1} m^2 sr μm) and G_{mk} is the electronic gain of band k. The combined $A_k G_{mk}$ can be found for each band in the head file of images (Table S1). Then the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes Model (Perkins *et al*., 2005), which allows to correct both additive and multiplicative atmospheric effects, was applied to conduct atmospheric correction and to convert at-satellite radiance into ground reflectance.

Conversion of multispectral vegetation indices

Many vegetation indices (VIs) have been developed in the past decades. Those suitable for SPOT 5 images are mostly 2-band VIs, such as the Normalized Difference Vegetation Index (NDVI) proposed by Rouse *et al*. (1973) and extended by Tucker (1979), the Simple Ratio index (Birth & McVey, 1968), the Soil-Adjusted Vegetation Index (SAVI; Huete, 1988), the Optimized Soil-Adjusted Vegetation Index (Rondeaux *et al*., 1996), the 2-band Enhanced Vegetation Index (EVI2; Jiang *et al*., 2008) and the Normalized Difference Infrared Index (NDII; Hardisky *et al*., 1983), among the others. These VIs were transformed from the atmospherically corrected SPOT 5 images. Furthermore, a new vegetation index, the Generalized Difference Vegetation Index (Wu, 2014) with power number of 2, 3 and 4 was tested

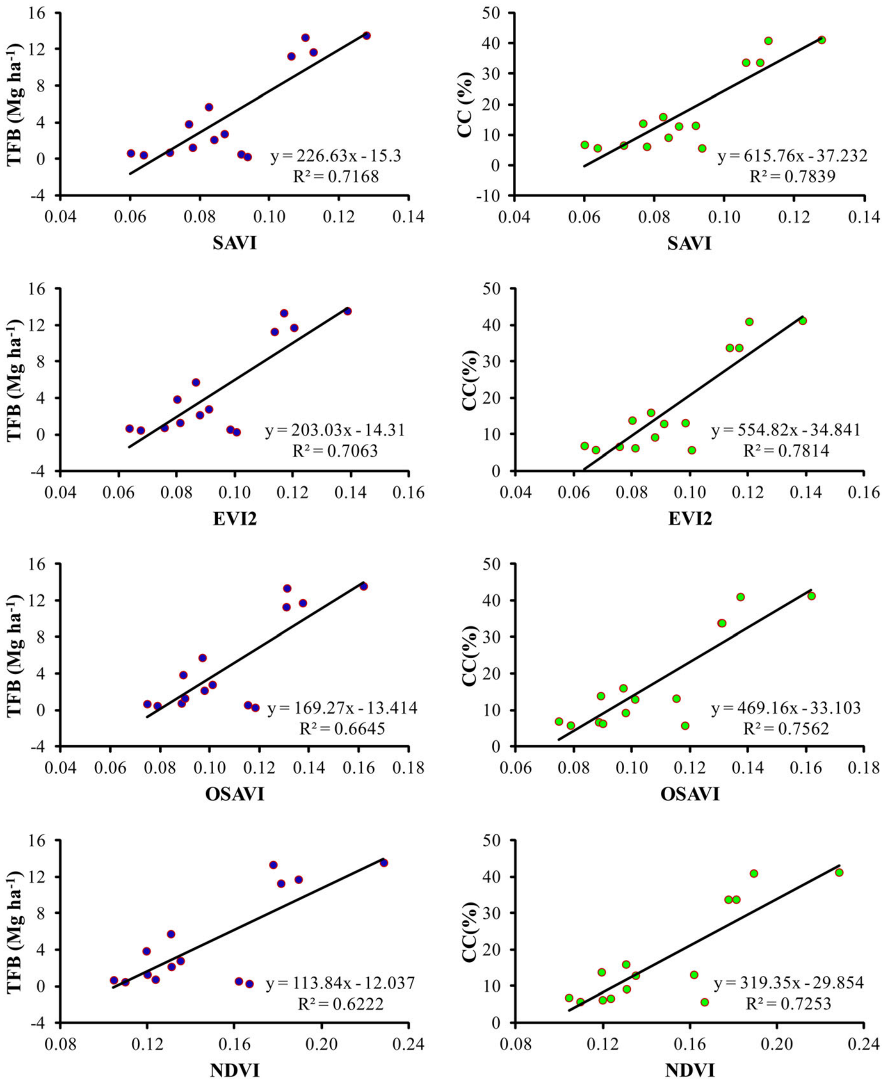

Figure 2. Scattering points revealing the correlation between VIs and TFB/CC for mature plantations. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

as it is considered to be sensitive to low vegetal biomes and to amplify the dynamic range of the vegetal information in dry land areas (Wu, 2014). The formulae of the tested vegetation indices are illustrated in Table I.

Although the acquired panchromatic fused bundles have higher resolution (2·5 m), during fusion or sharpening the original pixel values were changed. These images are suitable for visual interpretation or classification but not appropriate for biophysical spectral analysis, including vegetation indices. That's why only the images with ground resolution of 10 m were used for this study.

Spatial analysis

To understand the performance of the shrub plantations (*Atriplex*) in space and time, a cost-effective way is to couple the field measurements with the greenness indicators derived from satellite imagery, such as the vegetation indices. The procedure adopted in this study consisted of the following steps:

Grouping the field measurements. Field measurements were undertaken in plantations of different age and can be combined into three groups:

- Young plantations (2006/2007) with moderate biomass development (YA-1), 10 plots;
- Young plantations (2006/2007) with good biomass production (YA-2), 25 plots; and
- Old plantations (2000/2002) with mature biomass development (MA), 14 plots.

Interpolation of the climate data. Annual rainfall and 4 months' rainfall (4MRF) prior to image acquisition, that is November to February of 2003/2004, 2007/2008 and 2011/2012 from seven weather stations, were interpolated using the Kriging approach, assuming that vegetation greenness in images was related to the cumulative contribution of rainfall in the 3–4 antecedent months before image acquisition.

Extraction of vegetation indices and 4 months' rainfall data. The field measurement plots were spatially overlaid to the vegetation indices and to the interpolated rainfall data, and the values of NDVI, SAVI, EVI2, GDVI^2, GDVI^3, GDVI^4, NDII and 4MRF corresponding to the location of each sampling plot were extracted.

Correlation analysis and multiple linear regression modelling. A Pearson correlation analysis was applied to understand the relationship between the shrub biomass (TFB and TDB) and CC, the VIs and the 4MRF calculated for 2012.

Multiple linear regressions modelling at a confidence level of 95% was then performed to couple the shrub biomass with the VIs, or with the combination of VIs and 4MRF data, to construct biomass models.

Then, a test against the field measurement data was made to compare the relevance of the different models in terms of shrub biomass prediction. The most relevant one was selected for the successive shrub biomass characterization.

Selection of the herbaceous biomass models. Among the considered herbaceous biomass models, that of Devineau *et al*. (1986; Eq. 2) was selected. This model was developed using the annual maximum or peak NDVI (Tucker *et al*., 1985; Wu *et al*., 2013a). Our case is similar, because we are employing images acquired in the period February–March, representing the peak greenness of the herbaceous vegetation. The model equation is reported below:

$$B_H = 0.00216\ (100 * NDVI)^{1.7} \left(\mathrm{Mg\ ha}^{-1}\right) \qquad (2)$$

Where: B_H is dry herbaceous biomass.

Estimation of shrub and herbaceous biomass in the planted and non-planted (rangeland) sites. The selected shrub biomass model was applied to the VIs of 2004, 2008 and 2012 to estimate the dry shrub biomass production (TDB, including both wood and leave) in the planted and non-planted sites. Then, Equation 2 was applied to NDVI to acquire the herbaceous biomass in both planted and

Table I. Vegetation indices relevant for SPOT 5 images and used in this study

Index	Full name	Formula	References
NDVI	Normalized Difference Vegetation Index	$(\rho_{NIR}-\rho_R)/(\rho_{NIR}+\rho_R)$ ρ_{NIR} and ρ_R are, respectively, reflectance of the near infrared (NIR) and red (R) bands	Rouse *et al*. (1973) and Tucker (1979)
SR	Simple Ratio Index	ρ_{NIR}/ρ_R	Birth & McVey (1968)
SAVI	Soil-Adjusted Vegetation Index	$(1+L)(\rho_{NIR}-\rho_R)/(\rho_{NIR}+\rho_R+L)$ Low vegetation, $L=1$, intermediate, $L=0{\cdot}5$, and high $L=0{\cdot}25$	Huete (1988)
NDII	Normalized Difference Infrared Index	$(\rho_{NIR}\ +\ \rho_{MIR})/(\rho_{NIR}+\rho_{MIR})$ ρ_{MIR} is the reflectance of the middle infrared band (e.g. TM band 5 or SPOT 5 XS 4)	Hardisky *et al*. (1983)
OSAVI	Optimized Soil-Adjusted Vegetation Index	$(\rho_{NIR}-\rho_R)/(\rho_{NIR}+\rho_R+0.16)$	Rondeaux *et al*. (1996)
EVI2	Enhanced Vegetation Index 2	$2.5(\rho_{NIR}-\rho_R)/(\rho_{NIR}+2.4\rho_R+L)$ $L\ =\ 1$	Jiang *et al*. (2008)
GDVI	Generalized Difference Vegetation Index	$\left(\rho_{NIR}^{n}-\ \rho_{R}^{n}\right)/\left({}_{NIR}^{n}+\ \rho_{R}^{n}\right)$ n is the power number, a nonzero integer of the values of 1, 2, 3, 4… n.	Wu (2014)

non-planted sites based on the estimated natural vegetation cover data. For the plantations where field herbaceous vegetation cover measurement was not covered, an average of 14·1% calculated from the measured plantation plots was used.

Biomass weighting and combination. Biomass weighting (Wu *et al*., 2013a) was conducted based on the shrub and herbaceous cover in each planted and non-planted site. Taking a plantation polygon as an example, if the *Atriplex* and herbaceous covers are, respectively, 80% and 14·1%, we consider that the total biomass of a pixel in the given polygon is contributed, respectively, from the shrubs in 80% of the pixel and from the annual herbs in 14·1% of the pixel area. The combined dry biomass of the given pixel in the plantation polygon is calculated as $TDB*80\% + B_H*14{\cdot}1\%$. Similarly, for any pixel in the non-plantation polygon, if its natural shrub cover is 1%, the combined biomass would be $TDB*1\% + B_H*99\%$.

Total combined dry biomass comparison between planted and non-planted sites. After weighting and combining, the mean dry biomass production at polygon level was extracted, and a comparison was conducted between plantations and rangelands to understand the shrub growing performance and the effectiveness of the interventions to combat desertification.

RESULTS AND DISCUSSION

Correlation Coefficients

Correlation analysis illustrates that all the observed VIs except for NDII are strongly correlated with each other (Table II). This correlation indicates that the major information carried by different VIs derived from the combinations of near infrared and red bands is more or less the same, and VIs should be selectively inputted for biomass model development.

Table III shows that both total fresh and dry biomass, at hectare-level, are strongly correlated with CC, VIs and 4MRF in mature plantations (MA), moderately correlated in young plantations with good biomass development (YA-2) and weakly correlated in young plantations with moderate biomass development (YA-1). TFB seems better correlated with VIs than TDB, and SAVI is the best shrub biomass indicator followed by EVI2 in this case study, probably because both SAVI and EVI2 have taken soil influence into account. In order to better understand this aspect, the scattering of the data points for the different VIs versus TFB and CC are presented in Figure 2.

Surprisingly, the measured biomass of 2012 is also highly correlated with VIs of 2004 (Table III). Two reasons most likely concur to explain this phenomenon: one is that *Atriplex* shrub planted in 2000 had already developed a considerable biomass in 2004, as confirmed by local breeders; the other is that, due to higher rainfall, there might be more herbaceous vegetation mixed with *Atriplex* in spring 2004.

Remote Sensing Shrub Biomass Models

Multiple linear regression analysis allowed us to obtain two sets of biomass models for mature plantations (MA): VI-based and VI-4MRF-based (Tables IV and V). To evaluate which of the two sets of TDB models is more relevant for shrub biomass characterization, they were, respectively, applied back to SAVI, NDII of 2012, and 4MRF of 2011/2012 to predict shrub dry biomass. TDB-CC-4MRF and TDB-4MRF biomass models, despite of their high multiple R^2 values, have a clear overestimation and underestimation due to their heavy dependence on rainfall (Table V), which is completely dominated by the distribution density of weather stations.

As for the VI-based models, TFB seems slightly better correlated with VIs than TDB (Table IV). However, the TDB-VI models directly predict dry shrub biomass, of which the results look better than those of the TFB-VI model when compared with the field measured data.

For the set of VI-based biomass models (Table IV), the evaluation of the results performed using regression analysis reveals that the TDB-VIs model has higher accuracy ($R^2 = 0{\cdot}855$) than the TDB-CC-VIs model ($R^2 = 0{\cdot}741$) against ground measured biomass. Thus, the TDB-VIs model is more pertinent for predicting shrub biomass.

Biomass Growing Performance in Plantations and Rangelands

The polygon level shrub-herb combined mean dry biomass of the years 2008 and 2012 for both the planted and non-planted sites are shown in Table VI. The pixel-based combined mean dry biomass of both plantations and non-planted rangeland for 2012, taken as an example, is presented in Figure 3.

Table VI shows that the difference in the combined biomass production between plantations and rangelands is strong as the observed maxima reach, respectively, 6·57 and 0·25 Mg ha^{-1} in 2008, and 7·92 and 0·33 Mg ha^{-1} in 2012 in the planted and non-planted areas.

Table II. Pearson correlation matrix of all vegetation indices (VIs) of 2012 in the mature (MA) plantations

	NDVI	SAVI	OSAVI	EVI2	GDVI^2	GDVI^3	GDVI^4	NDII
NDVI	1·000							
SAVI	0·975	1·000						
OSAVI	0·997	0·990	1·000					
EVI2	0·984	0·999	0·995	1·000				
GDVI^2	1·000	0·976	0·997	0·985	1·000			
GDVI^3	0·999	0·977	0·997	0·986	1·000	1·000		
GDVI^4	0·997	0·978	0·996	0·986	0·998	0·999	1·000	
NDII	−0·205	−0·389	−0·273	−0·355	−0·206	−0·206	−0·207	1·000

Table III. Correlation coefficients between measured fresh/dry biomass and vegetation indices (Vis) of 2012 (YA-1, YA-2 and MA) and 2004 (MA). MA, Mature plantation; YA-1, Young plantation, moderate biomass development; YA-2, Young plantation, good biomass development

Plantation group	Biomass ($Mg\,ha^{-1}$)	CC	NDVI	GDVI^2	GDVI^3	GDVI^4	NDII	EVI2	SAVI	OSAVI	4MRF
YA-1 (2012)	TFB	−0·304	0·028	0·033	0·034	0·035	0·290	−0·125	0·155	−0·125	/
	TDB	−0·244	−0·158	−0·151	−0·154	−0·154	0·139	−0·058	−0·028	−0·058	/
YA-2 (2012)	TFB	0·347	0·474	0·486	0·502	0·519	−0·382	0·517	0·529	0·497	0·598
	TDB	0·343	0·408	0·416	0·426	0·437	−0·268	0·433	0·439	0·421	0·529
MA (2012)	TFB	0·972	0·789	0·787	0·784	0·780	−0·587	0·840	0·847	0·815	0·948
	TDB	0·951	0·742	0·740	0·737	0·733	−0·648	0·805	0·815	0·773	0·951
MA (2004)	TFB	0·972	0·905	0·895	0·878	0·855	0·331	0·923	0·924	0·914	0·923
	TDB	0·951	0·856	0·844	0·826	0·802	0·238	0·880	0·883	0·868	0·951

The biomass values in rangelands are generally low, reflecting a situation of widespread overgrazing (Figure 4a). An average increases from 0·12 $Mg\,ha^{-1}$ in 2008 to 0·22 $Mg\,ha^{-1}$ in 2012 (Table VI) can be observed. Although the two years show similar rainfall conditions (Figure 3), 2008 is the second year of a longer drought period. According to the information collected in the field, these conditions caused more intense and widespread overgrazing in 2008 compared to 2012. In 2012, the observed absolute rangeland productivity values range from 0·13 and 0·33 $Mg\,ha^{-1}$, corresponding, respectively, to the very degraded land of site 11 (Chehibat) and to the more productive soils of site 16 (in M'nabha).

The planted polygons show more complex behaviour (Table VI). If the youngest plantations are considered (those planted in 2007), the 2008 biomass values mainly depend on the recovery of the natural vegetation cover during the grazing exclusion period. The values range between 0·68 and 2·00 $Mg\,ha^{-1}$. They can be much higher compared with the surrounding non-planted land, reflecting the different rangeland resilience. The 2012 data, ranging from 1·60 to 3·95 $Mg\,ha^{-1}$, represent the biomass production of a 5-year-old plantation. At this age, the plantation is in full production, because in the study area, *Atriplex* plants reach their maximum green biomass production at an age of 4 to 7 years. Because of the effect of grazing and aridity, the herbaceous component of the observed biomass is much lower compared with the shrub one. So, the observed values mostly reflect the different plant development, which is related to both the site fertility and the management quality. Although the local authorities recommend grazing the plantations only after the end of the herb growing season, this indication is often not respected. Site 20 is an example of plantation implemented on harsh land conditions, where the mortality rate is high, and the plant development is limited (Figure 4b). On the other hand, less unfavourable and better managed polygons, such as site 28 (Figure 4c), show a considerable biomass production.

Two sites planted in 2006 (16 and 33) already show high values in 2008 (6·57 and 4·86 $Mg\,ha^{-1}$), just before the end of the grazing exclusion period, due to the combined effect of fast plant development and high herbaceous cover. These sites are located in very gently sloping areas and are the most productive of the study area. Site 16 is characterized by a thick, very hard, shallow calcareous crust, but after breaking by the ripper, the plant roots can easily reach the underlying deep and nutrient-rich layers. Site 33 has a relatively deep, clayey and fertile soil, formerly cropped for cereals and moderately affected by channelled water erosion. These two sites also show the highest biomass production in 2012, particularly site 16, where a prominent plant development compensates the herbs removal operated by grazing (Figure 4d).

Concerning the other 2006 polygons, sites 8 and 10 show good biomass values in 2012 and a relatively regular increase between 2008 and 2012. Site 32 is an exception, characterized by weaker development in both years.

Site 2 (2005) shows particularly low biomass values in 2008 (0·52 $Mg\,ha^{-1}$) compared with 2012 (2·03 $Mg\,ha^{-1}$). This is a documented case of mismanagement, where early grazing was carried out during the 2007 drought, before the end of the grazing exclusion period, with severe consequences on the plant development (Figure 4e). In the same period, the neighbouring site 1 was correctly managed (Figure 4f). The other 2005 site (14), along with the 2004 site (31), shows little or no increase between 2008 and 2012.

Table IV. Mature shrub biomass models obtained from the imagery of 2012

Models	Equations	Error	Multiple R^2
TFB-CC	TFB ($Mg\,ha^{-1}$) = −1·703 + 0·374CC	±1·281	0·945
TFB-VIs	TFB ($Mg\,ha^{-1}$) = −13·65 + 195·048SAVI − 22·856NDII	±2·576	0·795
TFB-SAVI	TFB ($Mg\,ha^{-1}$) = −15·30 + 226·631SAVI	±2·897	0·717
TDB-VIs	TDB ($Mg\,ha^{-1}$) = −6·481 + 97·199SAVI − 16·106NDII	±1·417	0·793
TDB-SAVI	TDB ($Mg\,ha^{-1}$) = −7·644 + 119·452SAVI	±1·729	0·664
TDB-CC-VIs	TDB ($Mg\,ha^{-1}$) = −0·589 − 9·396NDII + 0·176CC	±0·740	0·944
CC-VIs	CC = −37·232 + 615·76SAVI	±6·576	0·784

Table V. Rainfall-related shrub biomass models

Models[a]	Equations	Error	Multiple R^2
TFB-CC-4MRF	TFB ($Mg\,ha^{-1}$) = −210·036 + 0·164CC + 2·178RF	±1·005	0·969
TFB-4MRF	TFB ($Mg\,ha^{-1}$) = −360·992 + 3·758RF	±1·155	0·955
TDB-4MRF	TDB ($Mg\,ha^{-1}$) = −193·599 + 2·019RF	±0·847	0·919
CC-VI-4MRF	CC (%) = −740·312 + 93·937NDVI + 7·642RF	±3·342	0·949

[a]4MRF is expressed in RF in equations.

When the *Atriplex* plants are about 10 years old, they become senescent, produce less biomass and their woody fraction increases consistently. In fact, the highest average increase in biomass from 2008 to 2012 was observed for the 2006 plantations (1·69 $Mg\,ha^{-1}$). For this reason, to better record the plant life cycle curve, the 2004 image was also processed for the oldest plantation polygons (sites 0, 3, 34 and 11). As discussed in the methods section, the biomass calculation for that year is less accurate.

The 2002 site (11) shows a high biomass value in 2004 (4·35 $Mg\,ha^{-1}$), a performance comparable with the second best site of 2006 (33). Although the soil fertility of site 11 is lower, rainfall conditions during the 2 years of grazing exclusion were favourable (236 and 283 mm compared with an average of 202 mm). During the following years, site 11 was subjected to intense grazing by the local breeders, particularly during the mentioned 2007–2008 drought period. The behaviour of site 3 (planted in 2000) is similar, but with stronger decrease in 2008, and lower recovery in 2012, associated to advanced senescence conditions (Figure 4g).

Site 34 constitutes an extraordinary success case. Here, because of favourable soil and rainfall conditions, and careful management by the exploiting breeders, an exceptional biomass production (12·66 $Mg\,ha^{-1}$) was observed in 2004 (Figure 4h), which continues to be high in 2008 and 2012, in spite of the plant age.

Finally, site 0 constitutes a unique exception. It is the oldest one and has been subjected to new extensive planting works during the years 2006–2010. Old, dying plants were uprooted, and new seedlings were conducted, explaining the high value observed in 2012 (6·52 $Mg\,ha^{-1}$).

Benefits Generated by the Intervention to Combat Desertification

The objective of the rangeland rehabilitation interventions by means of *A. nummularia* plantations was twofold: mitigating land degradation and generating income for the local communities.

Previous studies analysed some of the ecological impacts of these plantations. Zucca *et al.* (2011) measured a significant increase in topsoil organic carbon under canopy (+32%), contrasted by a larger increase in sodium

Table VI. Comparison of the combined Mean Dry Biomass (MDB) between planted and non-planted (rangelands) areas in 2008 and 2012

ID	Plantation Year	Area (ha)	2012 MDB in plantations (A; $Mg\,ha^{-1}$)	2012 MDB in non-planted areas (B; $Mg\,ha^{-1}$)	2012 Difference between planted and non-planted (A – B; $Mg\,ha^{-1}$)	2008 MDB in plantations (C; $Mg\,ha^{-1}$)	2008 MDB in non-planted areas (D; $Mg\,ha^{-1}$)	2008 Difference between planted and non-planted (C – D; $Mg\,ha^{-1}$)	2008-2012 MDB increase in plantations (A – C; $Mg\,ha^{-1}$)	2004 MDB in plantations (E; $Mg\,ha^{-1}$)
20	2007	28·67	1·6024	0·1646	1·4378	0·6801	0·0814	0·5988	0·9223	
23	2007	56·84	2·7550	0·1650	2·5899	1·3879	0·0726	1·3153	1·3671	
25	2007	23·93	1·7460	0·1467	1·5993	0·7418	0·0962	0·6456	1·0042	
28	2007	10·27	3·9515	0·3072	3·6443	2·0094	0·1393	1·8701	1·9421	
8	2006	57·15	4·7901	0·2615	4·5286	3·1880	0·1257	3·0623	1·6021	
10	2006	68·58	4·2606	0·2038	4·0568	2·4202	0·1233	2·2969	1·8404	
32	2006	7·98	1·2158	0·1851	1·0306	0·2260	0·0929	0·1331	0·9898	
33	2006	2·98	7·5436	0·2037	7·3399	4·8556	0·1582	4·6974	2·6880	
16	2006	81·84	7·9187	0·3242	7·5945	6·5667	0·2545	6·3122	1·3520	
1	2005	17·14	4·1790	0·3326	3·8463	1·6718	0·1526	1·5192	2·5072	
2	2005	58·66	2·0343	0·1343	1·9000	0·5220	0·0666	0·4554	1·5123	
14	2005	27·93	4·6268	0·3106	4·3162	4·6056	0·2038	4·4017	0·0212	
31	2004	47·15	2·9603	0·2045	2·7558	2·0210	0·1342	1·8868	0·9392	
11	2002	79·99	2·4120	0·1251	2·2869	1·3612	0·0726	1·2886	1·0508	4·3462
3	2000	208·89	1·0685	0·1459	0·9225	0·3051	0·0516	0·2535	0·7634	2·8531
34	2000	173·75	5·5257	0·2224	5·3033	4·5325	0·1369	4·3957	0·9931	12·6578
0	1996	561·39	6·5183	0·2268	6·2915	2·6052	0·1117	2·4936	3·9130	8·0954
Mean			3·8299	0·2155	3·6144	2·3353	0·1220	2·2133	1·4946	

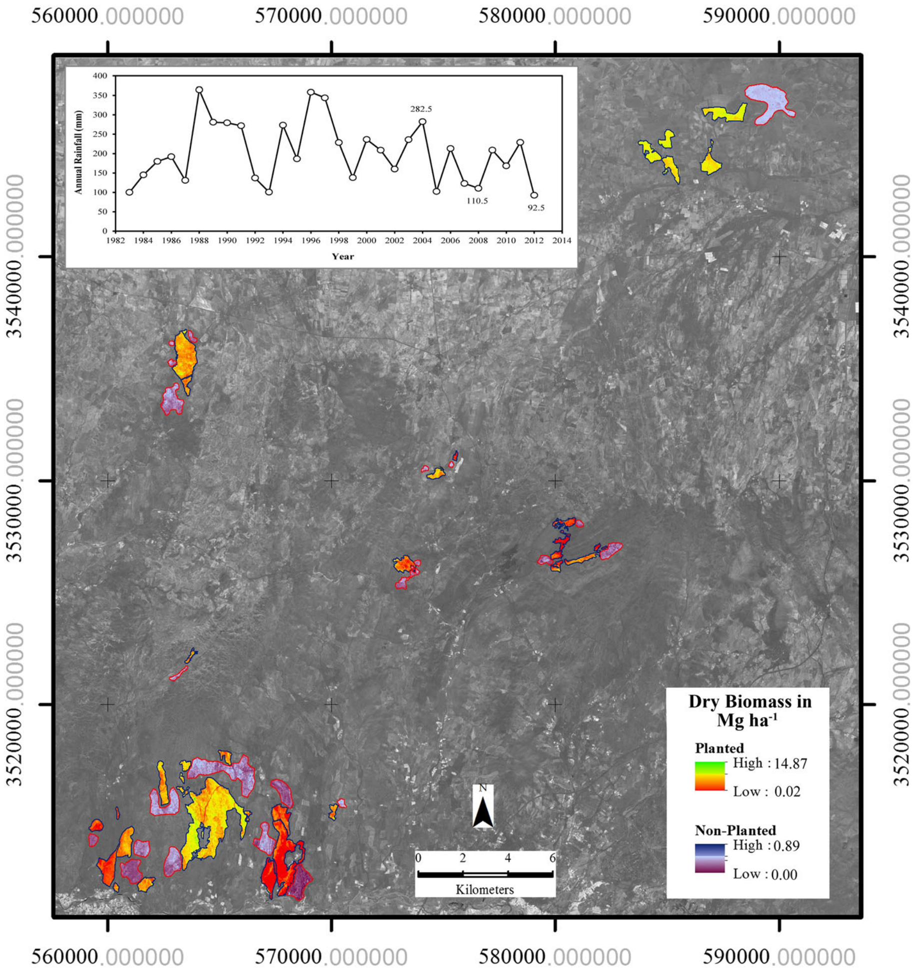

Figure 3. Combined shrub and herb dry biomass in planted (dark blue outline) and non-planted (red outline) areas in 2012. The grey background is the NDVI image dated 27 February 2012. Inset figure: Annual rainfall in the Ouled Dlim station (cumulated amount September–August). The annual rainfall of 2003–2004, 2007–2008 and 2011–2012 were labelled. The 2011–2012 value does not include precipitations after the end of February 2012. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

adsorption ratio (+139%). Zucca *et al*. (2013b) considered the ecological functions of the landscape by means of the landscape function analysis (LFA) approach, observing that the young and well-developed plantations have the stronger impacts on all the LFA indices, although these effects are mostly linked to the localized synergistic action of the plant-furrow association.

No study has been undertaken so far to quantify the economic benefits obtained by the local communities. This research, by means of the areal quantification of the fodder biomass provided by *Atriplex* plots, could provide proxy estimation.

Although the multitemporal analysis was mostly based on two images only, the high number of well documented plantation sites allowed for a detailed interpretation of the results obtained. Furthermore, by using images related to two dry years (2008 and 2012), characterized by relatively low herbaceous cover, it was possible to emphasize the contribution given by the fodder shrubs to the overall dry biomass production.

On average, in 2008 the plantation sites produced 2·21 Mg ha^{-1} of dry biomass more than the rangelands (Table VI). This difference became 3·61 Mg ha^{-1} in 2012. Well-managed plantations, without early and overgrazing, yielded greater differences, up to 7 Mg ha^{-1}. These values are not negligible, considering that, when the plantations are opened to grazing, the majority of the combined dry biomass is constituted by the *Atriplex* shrubs. However, the woody fraction of the shrubs (stem and branches), which is not available to sheep grazing, accounts for 50–95% of the total dry biomass (Zucca *et al*., 2013b). It increases with the plant age and is influenced by the site and management conditions. Poorly developed plantations, such as sites 20 and 25, which produced only around 1·5 Mg ha^{-1} more than the surrounding rangelands in 2012, can provide a significant fodder contribution only when the woody fraction is still low. When this value is high, as for sites 3 and 11 (respectively 90% and 95% in 2012; Zucca *et al*., 2013b), only very well-developed plantations can still constitute a fodder resource.

On the other hand, considering an average woody fraction of 75%, several 'good' plots showed important yearly production of green biomass, around 1 Mg ha^{-1} on average, and up to 2. This production level can be maintained for more or less

Figure 4. a) Sheep and goats feeding on herbs and shrubs in the study area rangelands. Photo by C. Zucca, March 2012. b) Site n° 20 (Ouled Nejim). Plant development (in the background) is limited by harsh land conditions. Photo by C. Zucca, February 2011. c) Site n° 28 (Draa Jebbar), showing considerable biomass production after 5 years, notwithstanding the harsh land conditions. Photo by C. Zucca, February 2011. d) Site n° 16 (M'nabha) has the highest combined biomass production in both 2008 and 2012. Photo by C. Zucca, February 2011. e) Site n° 2 (Menaa el Kahla) showed particularly low biomass values in 2008 due to early grazing during the 2007 drought. Photo by C. Zucca, January 2007. f) Site n° 1 (Dehar el Kidar), very close to site n° 2, and same age, but not subjected to early grazing in 2007. Photo by C. Zucca, January 2007. g) Site n° 3 (Kdadra), one of the oldest plantations, subjected to intense grazing. In 2012, most of the plants are senescent. Photo by C. Zucca, March 2012. h) Site n° 34 (El Ahntri). Exceptional development observed in the 4-year-old plantation. Photo by C. Zucca, February 2004. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr.

5 years, from the end of the grazing exclusion to the shrub senescence phase. This amount must be considered as a potential availability, because part of the fresh biomass is not reached by the grazing animals due to the height of the branches. In order to estimate the corresponding economic value, the experts of the local Direction Provincial de l'Agriculture (personal

communications) applied the price of a standard barley dose (3 Dirham/kg^{-1}), after multiplying the dry green *Atriplex* biomass by a factor of 0·45. So, 1 Mg ha^{-1} would correspond to a monetary value of 1,350 Dirham/ha^{-1} or around 120 Euro/ha^{-1} of potential income increase. However, the cost of the plantation establishment is around 4,500 Dirham/ha^{-1} or 405 Euro/ha^{-1}. Furthermore, the community loses income during the grazing exclusion period. Most likely, only in the case of the well-developed/well-managed plantations (whose production is above the average performance), the economic benefits are higher than the costs. The uncertain economic performance could be compensated by the positive ecological benefits arising from the interventions. However, this would require a long-term land management strategy to keep the restored land under protection (either by new plantations at the end of the plant life cycle or by grazing control). Otherwise, overgrazing 'as usual' would soon degrade the land again.

CONCLUSIONS

The remote sensing-based diachronic assessment of the areal biomass production of the studied interventions to combat desertification was achieved with the following conclusions.

Among the observed 2-band vegetation indices, SAVI was the most representative indicator of the *Atriplex nummularia* biomass production in large areas. The investigated biomass production dynamics were driven by the combined effects of soil and land conditions and grazing management, along the life cycle curve of the plant. Although the plant life cycle is short, well-developed and well-managed plantations could provide important fodder resources for several years, for example, with an annual production of 2·2–7·5 Mg ha^{-1} more than the surrounding rangelands, compensating the economic cost of the intervention. However, the plantation performance in several cases was not sustainable, mainly due to poor management, for example, early and/or over grazing. The research confirmed that management is a critical factor for the success of these restoration practices. To preserve the temporary ecological benefits generated by the interventions beyond the plantation life cycle, an effective long-term strategy would be needed. Furthermore, a more comprehensive social and microeconomic analysis would be suggested to perform a thorough cost-benefit analysis of the interventions in future.

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