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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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1   **ASSESSING THE EFFECTIVENESS OF LAND RESTORATION**

2   **INTERVENTIONS IN DRYLANDS BY MULTITEMPORAL REMOTE SENSING –**

3   **A CASE STUDY IN OULED DLIM (MARRAKECH, MOROCCO)**

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5   **ASSESSING LAND RESTORATION EFFECTIVENESS BY REMOTE SENSING**

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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.

Keywords: 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 (e.g., Symeonakis *et al*, 2014; Wang *et al*., 2014; Izzo *et al*., 2014). Desertification is particularly contributing to the depletion of soil resources in arid

58 and semiarid rangelands, increasingly threatened by population growth and overexploitation

59 (Cerdà & Lavee, 1999; Reynolds & Stafford Smith, 2002; Bedunah & Angerer, 2012).

60 The actions to combat desertification and land degradation can be broadly classified as

61 prevention, mitigation, and restoration interventions (Zucca *et al*., 2013a). The restoration

62 actions often involve the improvement of vegetation cover through, for example, the

63 (re)introduction of adapted species, the control of invasive species, and reforestation. Soil and

64 water conservation are examples of prevention and mitigation and may include a range of

65 approaches, among which improved soil management (Zhao *et al*., 2013; Mcdonagh &

66 Semalulu, 2014). Many technical options are available to recover the productivity of the

67 degraded rangelands, which are adapted to the different ecosystem conditions and local contexts

68 (King & Hobbs, 2006; Kinyua *et al*., 2009). They include passive (grazing exclosure; e.g.,

69 Gökbulak & Hizal, 2013), and active strategies, such as managed and rotational grazing, control

70 of shrub encroachment (Fulbright, 1996), vegetation reseeding (Wiedemann, 1987) and planting

71 of fodder shrubs and trees (Le Houérou, 2000).

72 The development of analytical methods for evaluating the success of the actions to combat

73 desertification is considered as crucial by the scientific community (Reynolds *et al*., 2007), and

74 is actively promoted by the UNCCD. However, land degradation and restoration processes may

75 produce complex and contrasting effects on the different ecosystem services involved, making

76 desertification assessment a challenging exercise (Sommer *et al*., 2011; Zucca *et al*., 2012).

77 Although an increasing number of scientific articles was devoted to this subject, particularly in

78 dry rangeland areas (Mekuria & Aynekulu, 2011; Thomaz & Luiz, 2012; Roa-Fuentes *et al*.,

79 2013; Kröpfl *et al*., 2013), few studies aimed at assessing the effectiveness of the interventions

80 to combat desertification (e.g., De Pina Tavarez et al., 2014). The available assessments were in

81 many cases carried out in a non-integrated way, e.g., by neglecting the social and economic

82 implications. Furthermore, they were often done on a small plot scale, and large scale

83 monitoring was rarely performed.

84 To conduct the evaluation over a wider area or region, the spatial observation tool, remote

85 sensing, should be employed (Rango *et al*., 2002) as satellites can macroscopically and

86 periodically observe the rather large area or region of interest, and obtain multitemporal and

87 even time-series land surface information (Wu, 2009; Wu *et al*., 2013a). Thanks to these

88 advantages, remote sensing has been widely applied to land characterization in dryland systems,

89 including land cover change, desertification monitoring, land degradation assessment, and

90 analysis of the of land management policies. That was achieved by applying the thresholding-

91 and-differencing and classification techniques on albedo (Courel *et al*., 1984; Otterman &

92 Tucker, 1985), or vegetation indices (Malo & Nicholson, 1990; Tucker *et al*., 1991;Evans &

93   Gerken, 2004; Wu, 2009; Wang *et al*., 2013;Wu *et al*., 2013b), taking the response of vegetation

94   to rainfall into account, or by spectral unmixing approach (Shoshany & Svoray, 2002; Hostert *et*

95   *al*., 2003) A number of studies have demonstrated the quantification of the photosynthetically

96   active herbaceous and shrub biomass production in rangelands and savannahs either by the

97   integrated spectral vegetation indices of the growing period (Tucker *et al*., 1985; Wessels *et al*.,

98   2007) or by the annual peak or maximum vegetation indices (Tucker *et al*., 1985; Wylie *et al*.,

99   1995; Bénié *et al*., 2005; Wu & De Pauw, 2010; Wu *et al*., 2013a, 2013b) through

100 coupling/modelling procedure. However, few remote sensing studies have focused on assessing

101 the effectiveness of human interventions, e.g., restoration/recovery through land management. It

102 is hence necessary to develop effective remote sensing-based approaches for such assessment in

103 a wider area, which can be, theoretically, undertaken by tracking the change in albedo or

104 greenness or change in biomass production. The latter is the direct indicator of land productivity

105 and is thus more relevant than the other indicators for this purpose.

106 This research targeted a specific type of rangeland rehabilitation intervention (fodder shrub

107 plantation) extensively carried out in Morocco to combat desertification. There, *Atriplex*

108 *nummularia* L. (Amaranthaceae; Oldman saltbush) plantations were widely implemented in

109 pilot sites, particularly in the Marrakech region since the 1990s. Such species, native to

110 Australia, was introduced in the northern Mediterranean area due to its resistance to aridity and

111 grazing, becoming the most important exotic shrub species utilized on a large scale to date in

112 the Mediterranean Basin (Le Houérou, 1992). It is palatable for livestock and provides a high

113 fodder production, green biomass for all-year grazing (Le Houérou, 1992).

114 The objective of this study was to develop a biomass-based remote sensing approach to assess

115 the dynamic performance and the effectiveness of those restoration interventions. Multitemporal

116 remote sensing data were obtained and field measurements were conducted for an integrated

117 analysis.

118

119   **STUDY AREA AND METHODS**

120

121 **Study area**

122 The study was conducted in pilot sites located in the Rural Municipalities of Ouled Dlim and

123 M'nabha (Marrakech region; Figure 1). The region is characterized by dry and hot summers

124 spanning from May to October. The average annual precipitation was 202 mm in Ouled Dlim

125 and 222 mm in Marrakech in the period 1983-2012. The annual potential evapotranspiration

126 (PET) calculated based on the FAO Penman-Monteith method (Allen *et al*., 1998) is about

127 1590-1820 mm in Marrakech. The aridity index (P/PET) is between 0.098 and 0.166 ("arid"

128 according to UNEP, 1997).

129   The central part of the area is characterized by the Jebilet relieves, where schist constitute the

130   main bedrock (Huvelin, 1970). Relieves are gently undulating. Soils are shallow and degraded

131   because of overgrazing and subsistence cropping. Although cereal harvesting (rainfed barley

132   and wheat) is carried out only in particularly rainy years, in some areas soil is ploughed almost

133   every year for fodder production. Sparse individuals of *Ziziphus lotus* L (Rhamnaceae). and rare

134   *Acacia horrida* L.(Mimosaceae), along with scattered shrub species typical of the degraded

135   pasturelands, such as *Peganum harmala* L. (Nitrariaceae), constitute the perennial vegetation

136   cover.

137   In the study area *Atriplex* plantations were established along linear furrows made through a

138   ripper. Plant density varies between around 1000 and 700 plants per ha (with somewhat regular

139   planting grids of, respectively, 3 m ×3 m or 4.5 m × 3 m). The intervention were mainly funded

140   and carried out by the local administration with the participation of the local communities,

141   which were stimulated to create cooperative organization to better manage the planted land.

142   Typical plantation time is February-April. Plots are opened to grazing only at the end of

143   summer of the third year, to protect the earliest plant development phase. During the following

144   years the users are recommended to implement controlled grazing strategies. However, due to

145   poor enforcement and monitoring, grazing management may vary significantly across the

146   different beneficiary communities.

147

148   *Atriplex* **biomass sampling**

149   Field sampling and measurement were conducted in 10 plantation sites on 21-29 March 2012.

150   The *Atriplex* biomass of each site was determined in 5 plots including four to five plants (or less,

151   in case of missing plants) belonging to two plantation lines, and covering a surface of 50-70 m^2,

152   depending on the planting density. The 5 plots were regularly located in a 2500 m^2 area (Figure

153   1). Plant size was measured by determination of the plant height and of two orthogonal plant

154   canopy maximum diameters (North-South and East-West). In consideration of the variability of

155   *A. nummularia* a plant shape was assigned to the plants: elliptic, spherical or hemispheric. The

156   canopy volume of the plants was calculated based on the recorded biometric data and to the

157   assigned plant shape. One plant per plot was sampled for fresh and dry biomass weight

158   determination. Data on fresh and dry biomass were used to calculate the mean quantity of

159   biomass per plot area, according to a procedure described in detail by Zucca *et al.* (2013b).

160   Overall, total fresh (wet) biomass (TFB; Mg ha^{-1}), total dry biomass (TDB; Mg ha^{-1}), and

161   canopy cover (CC; %) were determined in 49 plots. The centre location and the average biomass

162   of each plot were obtained and matched to the 10 m size pixels of SPOT images.

163

164 **Planted and non-planted polygons**

165 Polygons were drawn by means of the ArcGIS software to delimitate relatively large and

166 homogeneous plantations sites, both around the field plots and in additional plantations areas. In

167 all cases, control polygons of similar size were drawn in the surrounding non-planted (control)

168 rangeland areas (Figure 1). Care was taken in order to ensure the comparability between

169 plantation and reference polygons in term of bedrock, landform, and soils, based on previous

170 studies (Zucca & Previtali, 2007; Zucca *et al.*, 2011) and on the visual interpretation of the

171 remote sensing (RS) data.

172 The herbaceous cover was estimated along 50-m long linear transects in both the planted and

173 non-planted sites. The canopy cover of the woody wild shrubs (*Ziziphus lotus*) was visually

174 estimated for the non-planted sites based on high resolution satellite images.

175

176 **Satellite imagery and rainfall data.**

177 Three multitemporal SPOT 5 images including both multispectral (10 m resolution) and

178 panchromatic fused (sharpened) bundles (XS1, XS2 and XS3 with resolution of 2.5 m) dated 06

179 March 2004, 11 March 2008 and 27 February 2012 were obtained (Table S1). The period

180 February-March represents the peak greenness of the herbaceous vegetation. Monthly rainfall

181 data in the period 1983-2012 were obtained from the station of Ouled Dlim, in the study site,

182 and daily and monthly data from the stations of Marrakech, Safi, Essaouira, Kasba-Tadla, Beni

183 Mellal, and Nouasseur in the surrounding region. Annual rainfall data for the Ouled Dlim

184 station are shown in Figure 2.

185

186 **Image processing**

187

188 Atmospheric correction

189 The numerical level (or digital number) of each band (XS) of all SPOT 5 images was first

190 converted into at-satellite radiance (L_k) in line with the instruction of CNES (2012) by the

191 following equation (Eq. 1):

192 $X_k = A_k G_{mk} L_k$ or $L_k = X_k / A_k G_{mk}$ (1)

193 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

194 digital number); A_k is the absolute calibration coefficient (W^{-1} m^2 sr µm) and G_{mk} is the

195 electronic gain of band k. The combined $A_k G_{mk}$ can be found for each band in the head file of

196 images (Table S1). Then the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral

197 Hypercubes) Model (Perkins *et al.*, 2005), which allows to correct both additive and

198 multiplicative atmospheric effects, was applied to conduct atmospheric correction and to

199 convert at-satellite radiance into ground reflectance.

200

201 Conversion of multispectral vegetation indices

202 Many vegetation indices (VIs) have been developed in the past decades. Those suitable for

203 SPOT 5 images are mostly 2-band VIs such as the Normalized Difference Vegetation Index

204 (NDVI) proposed by Rouse *et al.* (1973) and extended by Tucker (1979), the Simple Ratio

205 index (SR; Birth & McVey; 1968), the Soil Adjusted Vegetation Index (SAVI; Huete, 1988),

206 the Optimized Soil-Adjusted Vegetation Index (OSAVI; Rondeaux *et al.*, 1996), the 2-band

207 Enhanced Vegetation Index (EVI2; Jiang *et al.*, 2008), and the Normalized Difference Infrared

208 Index (NDII; Hardisky *et al.*, 1983), among the others. These VIs were transformed from the

209 atmospherically corrected SPOT 5 images. Furthermore, a new vegetation index, the

210 Generalized Difference Vegetation Index (GDVI; Wu, 2014) with power number of 2, 3 and 4

211 was tested as it is considered to be sensitive to low vegetal biomes and to amplify the dynamic

212 range of the vegetal information in dryland areas (Wu, 2014). The formulae of the tested

213 vegetation indices are illustrated in Table 1.

214 Although the acquired panchromatic fused bundles have higher resolution (2.5 m), during

215 fusion or sharpening the original pixel values were changed. These images are suitable for

216 visual interpretation or classification but not appropriate for biophysical spectral analysis

217 including vegetation indices. That's why only the images with ground resolution of 10 m were

218 used for this study.

219

220 Spatial analysis

221 To understand the performance of the shrub plantations (*Atriplex*) in space and time, a cost-

222 effective way is to couple the field measurements with the greenness indicators derived from

223 satellite imagery, such as the vegetation indices. The procedure adopted in this study consisted

224 of the following steps:

225 *Grouping the field measurements*

226 Field measurements were undertaken in plantations of different age, and can be combined into

227 three groups:

228 • Young plantations (2006/2007) with moderate biomass development (YA-1), 10 plots;

229 • Young plantations (2006/2007) with good biomass production (YA-2), 25 plots; and

230 • Old plantations (2000/2002) with mature biomass development (MA), 14 plots.

231 *Interpolation of the climate data*

232 Annual rainfall and four months' rainfall (4MRF) prior to image acquisition, i.e. November to

233 February of 2003/2004, 2007/2008 and 2011/2012 from seven weather stations, were

234 interpolated using the Kriging approach, assuming that vegetation greenness in images was

235 related to the cumulative contribution of rainfall in the 3-4 antecedent months before image

236 acquisition.

237 *Extraction of vegetation indices (VIs) and rainfall (4MRF) data*

238 The field measurement plots were spatially overlaid to the vegetation indices and to the

239 interpolated rainfall data, and the values of NDVI, SAVI, EVI2, GDVI^2, GDVI^3, GDVI^4,

240 NDII, and 4MRF corresponding to the location of each sampling plot were extracted.

241 *Correlation analysis and multiple linear regression modelling*

242 A Pearson correlation analysis was applied to understand the relationship between the shrub

243 biomass (TFB and TDB) and CC, the VIs, and the 4MRF calculated for 2012.

244 Multiple linear regressions modelling at a confidence level of 95% was then performed to

245 couple the shrub biomass with the VIs, or with the combination of VIs and 4MRF data, to

246 construct biomass models.

247 Then, a test against the field measurement data was made to compare the relevance of the

248 different models in terms of shrub biomass prediction. The most relevant one was selected for

249 the successive shrub biomass characterization.

250 *Selection of the herbaceous biomass models*

251 Among the considered herbaceous biomass models, that of Devineau *et al*. (1986; Eq. 2) was

252 selected. This model was developed using the annual maximum or peak NDVI (Tucker *et al*.,

253 1985; Wu *et al*., 2013a). Our case is similar, since we are employing images acquired in the

254 period February-March, representing the peak greenness of the herbaceous vegetation. The

255 model equation is reported below:

256 $\qquad B_H = 0.00216 \ (100*NDVI)^{1.7} \ (\text{Mg ha}^{-1})$ $\qquad\qquad\qquad$ (2)

257 where B_H is dry herbaceous biomass.

258 *Estimation of shrub and herbaceous biomass in the planted and non-planted (rangeland) sites*

259 The selected shrub biomass model was applied to the VIs of 2004, 2008 and 2012 to estimate

260 the dry shrub biomass production (TDB, including both wood and leave) in the planted and non-

261 planted sites. Then, Eq.2 was applied to NDVI to acquire the herbaceous biomass in both

262 planted and non-planted sites based on the estimated natural vegetation cover data. For the

263 plantations where field herbaceous vegetation cover measurement was not covered, an average

264 of 14.1% calculated from the measured plantation plots was used.

265 *Biomass weighting and combination*

266   Biomass weighting (Wu *et al.*, 2013a) was conducted based on the shrub and herbaceous cover

267   in each planted and non-planted site. Taking a plantation polygon as an example, if the *Atriplex*

268   and herbaceous covers are respectively 80% and 14.1%, we consider that the total biomass of a

269   pixel in the given polygon is contributed respectively from the shrubs in 80% of the pixel and

270   from the annual herbs in 14.1% of the pixel area. The combined dry biomass of the given pixel

271   in the plantation polygon is calculated as *TDB*80% + B_H*14.1%.* Similarly, for any pixel in the

272   non-plantation polygon, if its natural shrub cover is 1%, the combined biomass would be

273   *TDB*1% + B_H*99%.*

274   *Total combined dry biomass comparison between planted and non-planted sites*

275   After weighting and combination, the mean dry biomass production at polygon level was

276   extracted and a comparison was conducted between plantations and rangelands to understand

277   the shrub growing performance and the effectiveness of the interventions to combat

278   desertification.

279

280   **RESULTS AND DISCUSSION**

281   **Correlation coefficients**

282   Correlation analysis illustrates that all the observed VIs except for NDII are strongly correlated

283   with each other (Table 2). This correlation indicates that the major information carried by

284   different VIs derived from the combinations of near infrared (NIR) and red (R) bands is more or

285   less the same and VIs should be selectively input for biomass model development.

286   Table 3 shows that both total fresh and dry biomass, at hectare-level, are strongly correlated

287   with CC, VIs and 4MRF in mature plantations (MA), moderately correlated in young

288   plantations with good biomass development (YA-2), and weakly correlated in young plantations

289   with moderate biomass development (YA-1). TFB seems better correlated with VIs than TDB,

290   and SAVI is the best shrub biomass indicator followed by EVI2 in this case study, probably

291   because both SAVI and EVI2 have taken soil influence into account. In order to better

292   understand this aspect, the scattering of the data points for the different VIs vs. TFB and CC are

293   presented in Figure 2.

294   Surprisingly, the measured biomass of 2012 is also highly correlated with VIs of 2004 (Table 3).

295   Two reasons most likely concur to explain this phenomenon: one is that *Atriplex* shrub planted

296   in 2000 had already developed a considerable biomass in 2004, as confirmed by local breeders;

297   the other is that, due to higher rainfall, there might be more herbaceous vegetation mixed with

298   *Atriplex* in spring 2004 (also see subsection 3.4).

299

300   **Remote sensing shrub biomass models**

301 Multiple linear regression analysis allowed us to obtain two sets of biomass models for mature

302 plantations (MA): VI-based and VI-4MRF-based (Tables 4 and 5). To evaluate which of the two

303 sets of TDB models is more relevant for shrub biomass characterization, they were respectively

304 applied back to SAVI, NDII of 2012, and 4MRF of 2011/2012 to predict shrub dry biomass.

305 TDB-CC-4MRF and TDB-4MRF biomass models, despite of their high multiple R^2 values,

306 have a clear over- and underestimation due to their heavy dependence on rainfall (Table 5),

307 which is completely dominated by the distribution density of weather stations.

308 As for the VI-based models, TFB seems slightly better correlated with VIs than TDB (Table 4).

309 However, the TDB-VI models directly predict dry shrub biomass, of which the results look

310 better than those of the TFB-VI model when compared with the field measured data.

311 For the set of VI-based biomass models (Table 4), the evaluation of the results performed using

312 regression analysis reveals that the TDB-VIs model has higher accuracy ($R^2 = 0.855$) than the

313 TDB-CC-VIs model ($R^2 = 0.741$) against ground measured biomass. Thus, the TDB-VIs model

314 is more pertinent for predicting shrub biomass.

315

316 **Biomass growing performance in plantations and rangelands**

317 The polygon-level shrub-herb combined mean dry biomass of the years 2008 and 2012 for both

318 the planted and non-planted sites are shown in Table 6. The pixel-based combined mean dry

319 biomass (MDB) of both plantations and non-planted rangeland for 2012, taken as an example, is

320 presented in Figure 3.

321 Table 6 shows that the difference in the combined biomass production between plantations and

322 rangelands is strong as the observed maxima reach respectively 6.57 and 0.25 Mg ha^{-1} in 2008,

323 and 7.92 and 0.33 Mg ha^{-1} in 2012 in the planted and non-planted areas.

324 The biomass values in rangelands are generally low, reflecting a situation of widespread

325 overgrazing (Figure 4a). An average increases from 0.12 Mg ha^{-1} in 2008 to 0.22 Mg ha^{-1} in

326 2012 (Table 6) can be observed. Although the two years show similar rainfall conditions (Figure

327 3), 2008 is the second year of a longer drought period. According to the information collected in

328 the field, these conditions caused more intense and widespread overgrazing in 2008 compared to

329 2012. In 2012 the observed absolute rangeland productivity values range from 0.13 and 0.33 Mg

330 ha^{-1}, corresponding, respectively, to the very degraded land of site 11 (Chehibat), and to the

331 more productive soils of site 16 (in M'nabha).

332 The planted polygons show more complex behaviour (Table 6). If the youngest plantations are

333 considered (those planted in 2007), the 2008 biomass values mainly depend on the recovery of

334 the natural vegetation cover during the grazing exclusion period. The values range between 0.68

335 and 2.00 Mg ha^{-1}. They can be much higher compared to the surrounding non-planted land,

336   reflecting the different rangeland resilience. The 2012 data, ranging from 1.60 to 3.95 Mg ha^{-1},

337   represent the biomass production of a 5 years old plantation. At this age the plantation is in full

338   production, since in the study area *Atriplex* plants reach their maximum green biomass

339   production at an age of 4 to 7 years. Due to the effect of grazing and aridity, the herbaceous

340   component of the observed biomass is much lower compared to the shrub one. So, the observed

341   values mostly reflect the different plant development, which is related to both the site fertility

342   and the management quality. Although the local authorities recommend grazing the plantations

343   only after the end of the herb growing season, this indication is often not respected. Site 20 is an

344   example of plantation implemented on harsh land conditions, where the mortality rate is high,

345   and the plant development limited (Figure 4b). On the other hand, less unfavourable and better

346   managed polygons such as site 28 (Figure 4c) show a considerable biomass production.

347   Two sites planted in 2006 (16 and 33) already show high values in 2008 (6.57 and 4.86 Mg ha^{-1}),

348   just before the end of the grazing exclusion period, due to the combined effect of fast plant

349   development and high herbaceous cover. These sites are located in very gently sloping areas and

350   are the most productive of the study area. Site 16 is characterized by a thick, very hard, shallow

351   calcareous crust, but after breaking by the ripper, the plant roots can easily reach the underlying

352   deep and nutrient-rich layers. Site 33 has a relatively deep, clayey and fertile soil, formerly

353   cropped for cereals and moderately affected by channelled water erosion. These two sites also

354   show the highest biomass production in 2012, particularly site 16, where a prominent plant

355   development compensates the herbs removal operated by grazing (Figure 4d).

356   Concerning the other 2006 polygons, sites 8 and 10 show good biomass values in 2012, and a

357   relatively regular increase between 2008 and 2012. Site 32 is an exception, characterized by

358   weaker development in both years.

359   Site 2 (2005) shows particularly low biomass values in 2008 (0.52 Mg ha^{-1}) compared to 2012

360   (2.03 Mg ha^{-1}). This is a documented case of mismanagement, where early grazing was carried

361   out during the 2007 drought, before the end of the grazing exclusion period, with severe

362   consequences on the plant development (Figure 4e). In the same period, the neighbouring site 1

363   was correctly managed (Figure 4f). The other 2005 site (14), along with the 2004 site (31), show

364   little or no increase between 2008 and 2012.

365   When the *Atriplex* plants are about 10 years old, they become senescent, produce less biomass,

366   and their woody fraction increases consistently. In fact, the highest average increase in biomass

367   from 2008 to 2012 was observed for the 2006 plantations (1.69 Mg ha^{-1}). For this reason, to

368   better record the plant life cycle curve, the 2004 image was also processed for the oldest

369   plantation polygons (sites 0, 3, 34, and 11). As discussed in the methods section, the biomass

370   calculation for that year is less accurate.

371 The 2002 site (11) shows a high biomass value in 2004 (4.35 Mg ha^{-1}), a performance

372 comparable to the second best site of 2006 (33). Although the soil fertility of site 11 is lower,

373 rainfall conditions during the two years of grazing exclusion were favourable (236 and 283 mm

374 compared to an average of 202 mm). During the following years site 11 was subjected to intense

375 grazing by the local breeders, particularly during the mentioned 2007-2008 drought period. The

376 behaviour of site 3 (planted in 2000) is similar, but with stronger decrease in 2008, and lower

377 recovery in 2012, associated to advanced senescence conditions (Figure 4g).

378 Site 34 constitutes an extraordinary success case. Here, due to favourable soil and rainfall

379 conditions, and careful management by the exploiting breeders, an exceptional biomass

380 production (12.66 Mg ha^{-1}) was observed in 2004 (Figure 4h), which continues to be high in

381 2008 and 2012, in spite of the plant age.

382 Finally, site 0 constitutes a unique exception. It is the oldest one, and has been subjected to new

383 extensive planting works during the years 2006-2010. Old, dying plants were uprooted, and new

384 seedlings were conducted, explaining the high value observed in 2012 (6.52 Mg ha^{-1}).

385

386 **Benefits generated by the intervention to combat desertification**

387 The objective of the rangeland rehabilitation interventions by means of *A. nummularia*

388 plantations was twofold: mitigating land degradation and generating income for the local

389 communities.

390 Previous studies analyzed some of the ecological impacts of these plantations. Zucca *et al.*

391 (2011) measured a significant increase in topsoil organic carbon under canopy (+32%),

392 contrasted by a larger increase in sodium adsorption ratio (+139%). Zucca *et al.* (2013b)

393 considered the ecological functions of the landscape by means of the landscape function

394 analysis (LFA) approach, observing that the young and well developed plantations have the

395 stronger impacts on all the LFA indices, although these effects are mostly linked to the localized

396 synergistic action of the plant-furrow association.

397 No study has been undertaken so far to quantify the economic benefits obtained by the local

398 communities. This research, by means of the areal quantification of the fodder biomass provided

399 by *Atriplex* plots, could provide a proxy estimation.

400 Although the multitemporal analysis was mostly based on two images only, the high number of

401 well documented plantation sites allowed for a detailed interpretation of the results obtained.

402 Furthermore, by using images related to two dry years (2008 and 2012), characterized by

403 relatively low herbaceous cover, it was possible to emphasize the contribution given by the

404 fodder shrubs to the overall dry biomass production.

405 On average, in 2008 the plantation sites produced 2.21 Mg ha^{-1} of dry biomass more than the

406 rangelands (Table 6). This difference became 3.61 Mg ha^{-1} in 2012. Well managed plantations,

407 without early and overgrazing, yielded greater differences, up to 7 Mg ha^{-1}. These values are not

408 negligible, considering that, when the plantations are opened to grazing, the majority of the

409 combined dry biomass is constituted by the *Atriplex* shrubs. However, the woody fraction of the

410 shrubs (stem and branches), which is not available to sheep grazing, accounts for 50 to 95% of

411 the total dry biomass (Zucca *et al.*, 2013b). It increases with the plant age and is influenced by

412 the site and management conditions. Poorly developed plantations, such as sites 20 and 25,

413 which produced only around 1.5 Mg ha^{-1} more than the surrounding rangelands in 2012, can

414 provide a significant fodder contribution only when the woody fraction is still low. When this

415 value is high, as for sites 3 and 11 (respectively 90% and 95% in 2012; Zucca *et al.*, 2013b),

416 only very well developed plantations can still constitute a fodder resource.

417 On the other hand, considering an average woody fraction of 75%, several "good" plots showed

418 important yearly production of green biomass, around 1 Mg ha^{-1} on average, and up to 2. This

419 production level can be maintained for more or less 5 years, from the end of the grazing

420 exclusion to the shrub senescence phase. This amount must be considered as a potential

421 availability, because part of the fresh biomass is not reached by the grazing animals due to the

422 height of the branches. In order to estimate the corresponding economic value, the experts of the

423 local DPA (Direction Provincial de l'Agriculture; personal communications) applied the price

424 of a standard barley dose (3 Dirham/kg), after multiplying the dry green *Atriplex* biomass by a

425 factor of 0.45. So, 1 Mg ha^{-1} would correspond to a monetary value of 1350 Dirham/ha, or

426 around 120 Euro/ha of potential income increase. However, the cost of the plantation

427 establishment is around 4500 Dirham/ha, or 405 Euro/ha. Furthermore, the community loses

428 income during the grazing exclusion period. Most likely, only in the case of the well developed

429 /well managed plantations (whose production is above the average performance) the economic

430 benefits are higher than the costs. The uncertain economic performance could be compensated

431 by the positive ecological benefits arising from the interventions. However, this would require a

432 long term land management strategy to keep the restored land under protection (either by new

433 plantations at the end of the plant life cycle, or by grazing control). Otherwise, overgrazing "as

434 usual" would soon degrade the land again.

435

436   **CONCLUSIONS**

437 The remote sensing-based diachronic assessment of the areal biomass production of the studied

438 interventions to combat desertification was achieved with the following conclusions.

439 Among the observed 2-band vegetation indices, SAVI was the most representative indicator of

440 the *Atriplex nummularia* biomass production in large areas. The investigated biomass

441 production dynamics were driven by the combined effects of soil and land conditions and

442 grazing management, along the life cycle curve of the plant. Although the plant life cycle is

443 short, well developed and well managed plantations could provide important fodder resources

444 for several years, e.g. with an annual production of 2.2-7.5 Mg ha^{-1} more than the surrounding

445 rangelands, compensating the economic cost of the intervention. However, the plantation

446 performance in several cases was not sustainable, mainly due to poor management, for example

447 early and/or over grazing. The research confirmed that management is a critical factor for the

448 success of these restoration practices. To preserve the temporary ecological benefits generated

449 by the interventions beyond the plantation life cycle, an effective long term strategy would be

450 needed. Furthermore, a more comprehensive social and micro-economic analysis would be

451 suggested to perform a thorough cost-benefit analysis of the interventions in future.

452

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638

640   Table 1: 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, $L = 0.5$, and high $L = 0.25$	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	$(\rho_{NIR}^n - \rho_R^n)/(\rho_{NIR}^n + \rho_R^n)$ n is the power number, a non-zero integer of the values of 1, 2, 3, 4... n.	Wu (2014)

645   Table 2: 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

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648   Table 3: Correlation coefficients between measured fresh/dry biomass and vegetation indices (Vis) of

649   2012 (YA-1, YA-2, and MA) and 2004 (MA). MA, Mature plantation; YA-1, Young plantation, moderate

650   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

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654   Table 4: 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

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657   Table 5: Rainfall-related shrub biomass models

Models[1]	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

658   [1]4MRF is expressed in RF in equations.

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Table 6: 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 captions

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.

Figure 2: Scattering points revealing the correlation between VIs and TFB/CC for mature plantations.

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 Feb.27, 2012. Inset figure: Annual rainfall in the Ouled Dlim station (cumulated amount September to 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.

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 four year old plantation. Photo by C. Zucca, February 2004.