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Non-destructive dry matter estimation of *Alhagi sparsifolia* vegetation in a desert oasis of Northwest China

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Abstract.
Question: Can above-ground biomass of naturally growing *Alhagi sparsifolia* shrubs be estimated non-destructively?
Location: Qira oasis (37° 01' N, 80° 48' E, 1365 m a.s.l.) at the southern fringe of the Taklamakan desert, Xinjiang, NW China.
Methods: Two methods were compared to estimate above-ground biomass (AGB) of *Alhagi*. At first shrub AGB was estimated by manual ground measurements (called 'allometric approach') of length, width and height of 50 individuals. Subsequently regression equations were established between calculated shrub canopy volume and shrub AGB (r^2 = 0.96). These equations were used to calculate AGB from manual ground measurements in 20 sample plots within the *Alhagi* field. Secondly, kite-based colour aerial photography coupled with the use of a Geographic Information System (called 'GIS approach') was tested. First and second order polynomial regressions between AGB data of the 50 individual shrubs and their respective canopy area allowed to automatically calculate the AGB of all remaining shrubs covered by the photograph (r^2 = 0.92 to 0.96). The use of non-linear AGB regression equations required an automatised separation of shrubs growing solitary or in clumps. Separation criteria were the size and shape of shrub canopies.
Results: The allometric approach was more reliable but also more time-consuming than the GIS-based approach. The latter led to an overestimation of *Alhagi* dry matter in densely vegetated areas. However, this systematic error decreased with increasing size of the surveyed area. Future research in this field should focus on improvements of AGB estimates in areas of high shrub density.

Keywords: Aerial photography; Biomass monitoring; GIS; Image classification; Vegetation monitoring.

Abbreviations: AGB = Above-ground biomass; DM = Dry matter.

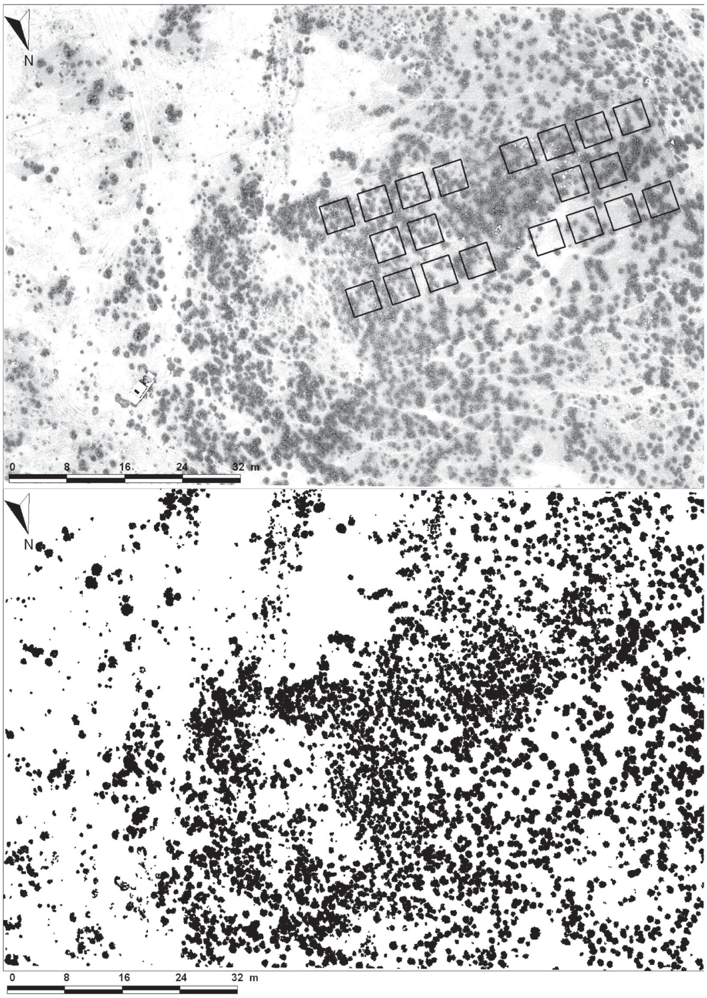
Introduction

River oases at the southern fringe of the Taklamakan desert in Xinjiang, NW China, the second largest desert in the world, are surrounded by a belt of indigenous vegetation that functions as a shelter against drifting sand. This function is indispensable for the oases, as NW winds prevail (Xia et al. 1993) and constantly transport silt from the desert towards the oases. The foreland vegetation is also an important component of the agricultural system of the oases because it is a major source of forage, fuel and construction wood, while it is grazed by sheep, goats and camels.

The protective function of the foreland vegetation is threatened by increasing overuse due to rapid population growth, and by an increasing use of water for irrigation of cropland in the oases where production is being intensified. The consequence is that large foreland areas are completely free of vegetation leading to sand encroachment of the agricultural land.

The effective protection of the foreland vegetation as an economic resource and a protective vegetation belt for the oasis cropland requires a quantitative understanding of its ecological resilience, in particular with respect to the amount of plant biomass that can be sustainably extracted each year. In the past research has focused on oasis cropland and virtually nothing is known about the effects of periodic cutting or grazing of the foreland vegetation on its productivity.

Within the framework of a broader study (Thomas et al. 2000) the work described here aims at developing and comparing non-destructive methods to determine Above-ground biomass (AGB) per unit area (biomass density) and annual biomass production of the foreland vegetation in August, the time of maximum AGB accumulation in the course of the annual growing period. The study focused on pure stands of *Alhagi sparsifolia*, a spiny, 1 m tall perennial herb of the *Fabaceae* which is



a
b

Fig. 1. a. Aerial photograph of *Alhagi sparsifolia* vegetation from ca. 250 m height with sample squares (above); **b.** polygon layer of *Alhagi* shrubs showing the results of a classification effort (below). Qira oasis, NW China.

unequally distributed in the foreland of the oases. Due to its high concentration of raw protein, it is a particularly valuable fodder for small ruminants and as such of particular importance for winter feeding of the large herds of the local farmers.

In principle the AGB of such shrubs can be estimated non-destructively either by ‘allometric regressions’ which are based on the basal area or the calculated crown volume (Nikolaev & Baimyradov 1987; Uso et al. 1997). Alternatively, true colour or infrared aerial images analysed within a Geographic Information System (‘GIS-approach’) can be used (Aparicio et al. 2000; Li et al. 1998). The usage of true colour photographs to estimate AGB is based on mapping the canopy greenness (Moraghan 1998; Blackmer & Schepers 1996). Studies in the West African Sahel showed that it was also possible to derive AGB of solitary *Guiera senegalensis* from the shrub canopy size determined on high resolution aerial images (Gerard & Buerkert 1999).

Material and Methods

Study site

The study was carried out near the desert research station of the Chinese Academy of Science in Cele (Qira) oasis (37°01' N, 80°48' E, 1365 m a.s.l. at the southern fringe of the Taklamakan desert in Xinjiang Autonomous Region, NW China. The climate is continental, with cold, dry winters and hot, dry summers. Mean annual temperature is 11.9 °C, annual potential evaporation is approximately 2600 mm and the annual sum of precipitation is 35.1 mm (Xia et al. 1993). Plant growth thus largely depends on water from melting snow which comes down from the Kunlun mountain range in large rivers. The experimental site comprised a naturally grown piece of foreland vegetation of 96 m × 66 m dominated by heterogeneously distributed *Alhagi sparsifolia* stands (Fig. 1). 20 test plots of size 4 m by 4 m are located on densely vegetated parts of this field.

Aerial photography

The lack of cold storage at the project site prevented the use of infrared films. Therefore true colour aerial photographs of the site were taken in August 2000 from a kite at a height of ca. 250 m (Fig. 1a). Attached to the kite was a remotely controlled standard 24 mm × 36 mm reflex-camera (Nikon F 601) equipped with a 50 mm lens and loaded with a Kodak 100 ISO colour negative film (Buerkert et al. 1996; Gerard et al. 1997). To avoid shaded areas on the photograph, all images were taken near midday. Because a differential global positioning system (DGPS) was not available, the images could not be geo-referenced. However, the photograph chosen for analysis covered four ground control points with known distances in-between. This allowed to compute the ground size of an image pixel.

Destructive harvest of sample shrubs

After taking the photograph in August 2000, 50 shrubs were marked on the image, measured for their largest and corresponding perpendicular diameters as well as for maximum shrub height and then harvested. Subsequent drying in a forced drought oven at 65 °C allowed the determination of total above-ground dry matter of each shrub. A total of 37 shrubs were measured, harvested and dried in the same manner in 1999, but no aerial photograph was taken.

Image processing

Initial efforts to extract shrub area from the photograph with standard classification methods or clustering failed because the colour of the shrub surfaces on the photograph was not uniform (Fig. 1a). The bush surface comprised a patchy pattern from light green to almost black tones. Therefore in a first step the red, green and blue channels of the image were classified within the 0-255 colour tone range. It was assumed that pixels represented *Alhagi* vegetation if the value of the blue band was below 120 and in addition the value of the green band was larger than the value of the red band.

To define single shrubs, the raster map was converted into a vector map by conglomerating neighbouring *Alhagi* pixels. Thereby more than 70 000 single polygons were created in the 96 m × 66 m field. Most of them were of a very small size and represented shadow areas within the shrubs (holes) or green reflections of the soil. To eliminate these, polygons with an area of less than 10 pixels (ca. 69 cm^2) were deleted. This led to a reduction of polygons to 2209 (Fig. 1b). Because many of the shrubs were growing closely together, in some areas it was not possible to distinguish single shrubs, which led to the creation of a network of connected shrub units subsequently referred to as 'clumps'.

Establishment of regression equations

Allometric approach

To optimize the allometric regression approach the following parameters were varied: (1) the mathematical model (linear, power or polynomial), (2) the data transformation (with or without transformation to natural logarithm) and (3) the method of determining the shrub volume or shrub projection area (two-dimensional: circle, ellipse and rectangle; three-dimensional: sphere, sphere cap and cube). Regressions were tested for significance ($p \leq 0.05$) by analysis of variance (ANOVA) and equation parameters by *t*-tests. Normal distribution of data was checked using the Kolmogorov-Smirnov test and was assumed if P for H_1 was > 0.05. Without transformation, residuals of shrub volumes were not normally distributed, therefore all volume data were transformed to their natural logarithm and linear equations were fitted using least-squares procedures. Correction factors (*CF*) for the bias introduced by logarithmic transformation were calculated according to Sprugel (1983) as:

$$CF = \exp\left(0.5SEE^2\right) \qquad (1)$$

with *SEE* = standard error of the estimate.

Homogeneity of variances was tested using the Levene Median test ($p > 0.05$). To test for autocorrelation of residuals, the Durbin-Watson coefficient was calculated (Anon. 2000). Equations with a coefficient between 1.5 and 2.5 were accepted. All r^2 values reported are adjusted for degrees of freedom of their respective sums of squares. SigmaPlot 2000 software (SPSS Science, Chicago, USA) was used for statistics.

GIS-based approach

Regression analyses between total dry matter of the 50 sample shrubs and the canopy area of these shrubs as derived from the aerial photograph led to linear and non-linear regression equations. A zero intercept was assumed because the computed intercept was negative. The use of a negative intercept would lead to a slightly better fit of the regression estimate ($r^2 = 0.928$ compared to 0.919 in the linear estimate) but also to negative AGB for small shrubs (< 0.048 m^2 in the linear estimate) which makes no practical sense.

For solitary shrubs a non-linear type of regression equation might be particularly useful because shrub height, which could not be detected from the aerial photograph, grows with shrub length and width. However, the non-linear regression equation for solitary shrubs should not be used for shrub clumps, because the height of shrub clumps appeared to be limited and only loosely related to the total canopy area of the clump. To also establish a regression equation for shrub clumps, 31 clumps were split by hand into 100 single bushes. These clumps were selected because their shape allowed easy identification and separation of individual component shrubs.

Subsequently, the dry matter of these single parts was computed using the non-linear equation for solitary shrubs and thereafter the AGB of the individual clump parts was summed up to compute the AGB of the shrub clump. This was based on the assumption that bush AGB of split clumps could be computed from the (non-linear) regression equation for solitary shrubs. A linear equation was established to predict the AGB of these 31 clumps based on their computed total canopy area (Fig. 2). Subsequently, this equation was used to estimate the AGB of the other shrub clumps.

This procedure helped to avoid the splitting of all shrub clumps into single shrubs. For most of the clumps the true number of single shrubs could not be detected, neither by hand nor automatically. However, it was still necessary to distinguish between solitary shrubs and shrub clumps. An algorithm was developed which separated shrub clumps according to size and shape of the canopy area. A shrub was assumed to be a 'solitary shrub', if its canopy area was less than 150 pixels (ca. 0.1 m^2) and a 'clump' if its canopy area was larger than 2 500 pixels (ca. 1.7 m^2). For canopies between these margins, the classification took also the shape of the shrub into account. Solitary shrubs tended to be compacter than shrub clumps (Fig. 3). To use this finding for further analysis a compactness indicator c was established by dividing the canopy area by the area of a circle comprising the shape. This method was first applied to compare the compactness of several European countries (Selkirk 1982). To distinguish solitary and connected shrubs (Fig. 3) a set of mathematically defined rules was used (Table 1). The rules were defined and optimized in a trial and error approach. Compared to other methods of shape approximation (Safar et al. 2000) this approach was easy to apply, needed low computational resources and when using area expressed in m^2 rather than in pixels it was rotation- and scale-independent.

Verification of regression equations

To test the reliability of the regression equations, these were tested with the 20 sample plots as well as for the entire 96 m × 66 m field and the thereby computed AGB values were compared. For the allometric estimates it was assumed, that shrubs belonged to a specific sample plot if their stem was located within the plot, although parts of the shrub crown might have grown outside the plot. For the GIS-based method it was impossible to exactly locate the stem position. Therefore it was decided to cut shrub canopy areas at the borderlines of the plots.

To estimate the shrub AGB on the entire 96 m × 66 m field with the allometric approach, a regression equation between shrub density and biomass density was established that was based on the data from the 20 sample plots. This equation was applied to the entire field by using a GIS-based estimate for the total number of shrubs, so that the measurement of diameters and height for each of the shrubs could be avoided.

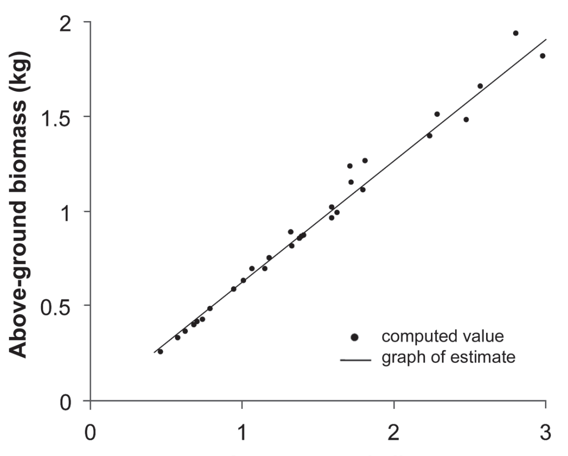


Fig. 2. Relationship between above-ground biomass (AGB) of artificially split and re-aggregated individual shrubs of *Alhagi sparsifolia* clumps and canopy area determined from an aerial photograph at Qira oasis, NW China.

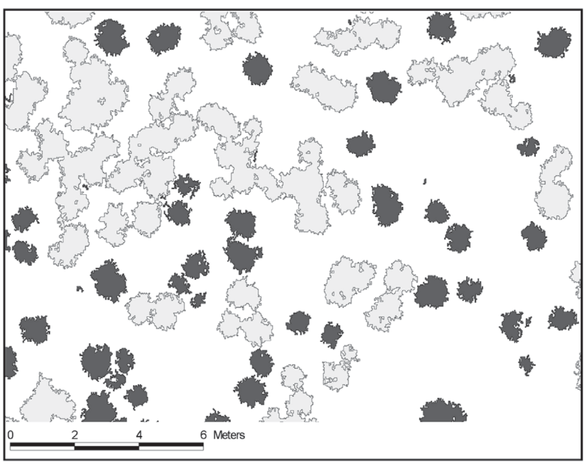


Fig. 3. Detail of the shrub polygon layer showing automatically detected solitary shrubs (dark grey coloured) and shrub clumps (light grey coloured) of *Alhagi sparsifolia* at Qira oasis, NW China.

Results

Regression equations for the harvested shrubs

The allometric approach and the GIS-based approach were both suitable to estimate the AGB of the harvested sample shrubs (Table 2). For the allometric approach AGB was closely correlated with shrub volume calculated as a sphere, with mean of shrub length, width and height as parameters. The regressions were statistically significant ($p \leq 0.001$) and met the requirements for regression analysis with respect to normal distribution, homogeneity of variances and autocorrelation of residuals. The slopes and offsets of the allometric regression equations for 1999 and 2000 were not significantly different using tests at $p \leq 0.05$. Therefore even dry weights of shrubs harvested in 2000 could be well predicted by the 1999 regression equation (Fig. 4, Table 2). Also in the GIS-based approach shrub AGB was highly correlated with the canopy area as detected from the aerial photograph (Fig. 5, Table 2).

Above-ground biomass of the sample squares

With the allometric approach an AGB of 52 kg was calculated for the 422 shrubs of the 20 sample plots. Average shrub density in the 20 sample squares was 1.32 ind.m^{-2} with a range from 0.3 to 2.6 ind.m^{-2}. Individual shrub AGB was between 71 and 376 g, and biomass density varied between 79 and 261 g.m^{-2}. Average biomass density of the 20 sample squares was 163 ± 9 g.m^{-2} (Table 3). Mean shrub AGB was inversely correlated with shrub density (Fig. 6a). This partly compensated for the effect of shrub density (g.m^{-2}) on biomass density (g.m^{-2}), so that biomass density was only weakly (but significantly) correlated to shrub density (Fig. 6b) according to:

$$\textit{Biomass density} = 40.4 \times \textit{Shrub density} + 109.3 \quad (2)$$

with adjusted $R^2 = 0.37$ and $P = 0.003$.

Using the GIS-based regression equations and the detected canopy areas of the shrubs AGB values of 73 kg (for the non-linear estimate) and 86 kg (for the linear estimate) were computed. About 86% of the biomass was growing in shrub clumps.

Table 1. Decision tree to distinguish between solitary shrubs of *Alhagi sparsifolia* and shrub clumps at Qira oasis, NW China.

Shape condition	Size condition		Decision
$c < 0.4$	size < 150 pixels	(≈ 0.10 m^2)	Solitary shrub
	size ≥ 150 pixels	(≈ 0.10 m^2)	Clump
$0.4 \leq c < 0.5$	size < 800 pixels	(≈ 0.55 m^2)	Solitary shrub
	size ≥ 800 pixels	(≈ 0.55 m^2)	Clump
$0.5 \leq c \leq 0.6$	size < 2000 pixels	(≈ 1.38 m^2)	Solitary shrub
	size ≥ 2000 pixels	(≈ 1.38 m^2)	Clump
$c > 0.6$	size < 2500 pixels	(≈ 1.73 m^2)	Solitary shrub
	size ≥ 2500 pixels	(≈ 1.73 m^2)	Clump

Table 2. Results of regression analysis between harvested above-ground biomass (AGB) of *Alhagi* shrubs and the canopy area computed from the aerial photograph (GIS-based approach) or shrub volume (allometric approach) at Qira oasis, NW China.

	Harvested shrubs	Estimate A	Estimate B	Estimate C	Estimate D	Estimate F
Description	50 harvested sample shrubs in year 2000	Function fitted to volume and AGB of shrubs harvested in 2000, allometric	Function fitted to volume and AGB of shrubs harvested in 1999, allometric	Linear function fitted to crown area and AGB of shrubs harvested in 2000, GIS-based	Non-linear function fitted to crown area and AGB of (solitary) shrubs harvested in 2000, GIS-based	Linear function fitted to canopy area and AGB of 31 shrub clumps, GIS-based
Type of regression equation	—-	ln (AGB) = a*ln(Volume)+b	ln (AGB) = a*ln(Volume)+b	AGB = a*Area	AGB = a*Area^2 + b*Area	AGB = a*Area
Units	—-	g (AGB) and cm^3 (Volume)	g (AGB) and cm^3 (Volume)	kg (AGB) and m^2 (Area)	kg (AGB) and m^2 (Area)	kg (AGB) and m^2 (Area)
Parameters	—-	a = 1.0349 b = –7.7455 CF = 1.0257	a = 0.9753 b = –7.0649 CF = 1.045	a = 0.7395	a = 0.2684 b = 0.4944	a = 0.6343
r^2 adjusted	—-	0.96	0.92	0.92	0.96	0.98
AGB range within the shrub samples (g)	10 - 1458	7 - 1397	8 - 1186	5 - 1142	3 - 1403	257 - 1939
Standard deviation (g)	273	261	224	244	275	457
Total AGB (g)	12 589	12 624	11 570	13 441	12 188	28 277

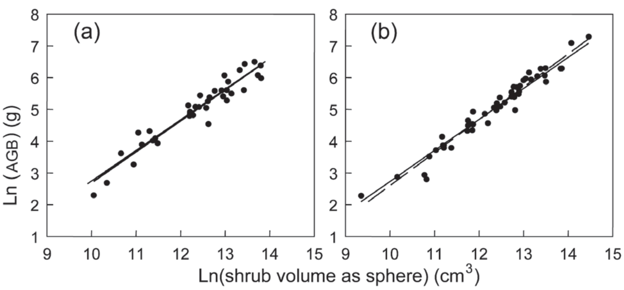


Fig. 4. a. Relationship between *Alhagi sparsifolia* shrub volume and their above-ground biomass (AGB) in August 1999 at Qira oasis, NW China; ● measured values; – linear regression equation, $r^2 = 0.92$, $p \leq 0.0001$; **b.** same as above but harvested in August 2000; $r^2 = 0.96$, $p \leq 0.0001$; dry weights of shrubs harvested in 2000 predicted by the 1999 regression equation.

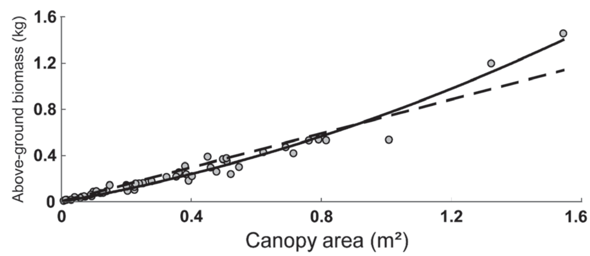


Fig. 5. Relationship between *Alhagi sparsifolia* canopy area (derived from the aerial photograph) and shrub above-ground biomass; ◦ measured; – quadratic regression equation; - - linear regression equation. Qira oasis, NW China.

Above-ground biomass of the entire field

On the aerial photograph 1,649 solitary bushes, covering a total area of 310 m^2 and 560 shrub clumps, covering a total area of 1044 m^2 were detected. Based on the average number of 4.33 shrubs per shrub clump for the 4 m × 4 m sample squares (Table 4) the total number of shrubs on the aerial photograph was estimated as 4.33 * 560 + 1649 = 4 076 shrubs. Shrub density in the 96 m × 66 m field therefore was 0.643 ind.m^{-2} and biomass density was estimated according to Eq. 2 as 135.3 g.m^{-2}.

Using this biomass density, the shrub AGB of the entire field was estimated as 0,1353 kg.m^{-2} * 6336 m^2 = 857 kg. Using the GIS-based approach AGB values of 858 kg (for the non-linear estimate) and 1 001 kg (for the linear estimate) were calculated. Irrespective of the type of equation shrub clumps comprised 77% of the shrub AGB of the field.

Time requirement

The initial establishment of the method required 5 man days for the allometric approach and 20 man days for the GIS-based approach. However, given that both approaches with their respective equations are now established and most likely can be reused, the future time requirements for the estimation of *Alhagi* AGB should be substantially smaller for GIS-based estimates compared with allometric measurements (Table 5).

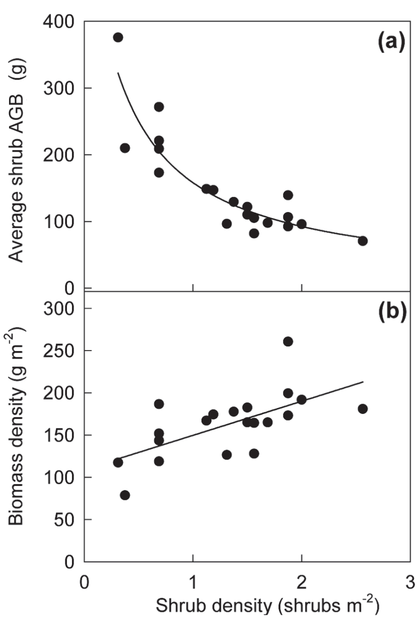


Fig. 6. Relationship between shrub density and average shrub weight of *Alhagi sparsifolia* in twenty 4 m × 4 m sample plots at Qira oasis, NW China. Adjusted r^2 of hyperbolic equation = 0.79, $p \leq 0.05$ **(a)**; Relationship between shrub density and biomass density; adjusted $r^2 = 0.37$, $p = 0.003$ **(b)**.

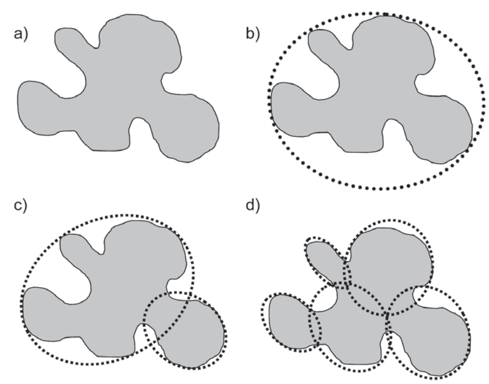


Fig. 7. Differences between GIS-detected shrub canopy area (gray colored) and computed crown projection area (dotted outline), assuming that the shrub consists of a solitary shrub **(b)**, that the shrub consists of a clump of two **(c)** or five **(d)** shrubs. Qira oasis, NW China.

Table 3. Shrub density, above-ground biomass and above-ground biomass density of *Alhagi sparsifolia* in the sample squares at Qira oasis, NW China (means ± se, n = 20).

	Shrub density (ind.m^{-2})	AGB (g)	AGB (g.m^{-2})
Mean	1.32 ± 0.13	150.1 ± 16.9	163 ± 9
Minimum	0.3	71	79
Maximum	2.6	376	261

Table 4. Estimation of average number of shrubs per clump from ground and GIS counts in sample squares of *Alhagi sparsifolia* at Qira oasis, NW China.

	Solitary shrubs	Shrub clumps
Total number of shrubs (manual ground count)	422	-
GIS estimate	110	71
Shrubs in clumps	312	
Shrubs per clump = 312 / 71 = 4.33		

Discussion

The high correlation of the different estimates of shrub AGB with true dry matter is encouraging. Because shrub clumps comprised over 77% of the AGB in the sample area, future research should be focused on these densely vegetated areas. Most of the 50 sample shrubs harvested in 2000 were solitary shrubs, whereas the 37 sample shrubs harvested in 1999 were representative for the 20 sample squares and therefore most of them were parts of shrub clumps.

The use of GIS-based regression equations requires the ability to distinguish between solitary shrubs and shrub clumps. In the linear regression equation, which does not distinguish between shrub types, the slope was 0.74. However, in the regression equation for clumps, established by splitting clumps into single shrubs and summing up the AGB derived from the non-linear estimate, the slope was only 0.63 (Table 2). Nevertheless, even the application of this clump specific estimate led to an overestimation of AGB in the densely vegetated sample squares (Table 6). This overestimation was largest in areas in which the average crown projection area of the shrubs was small. This is usually the case in the clumps where the space to extent the twigs horizontally is limited. The biomass density derived from the crown projection (allometric approach) remained nearly constant (Table 6). This leads to the assumption, that differences between allometrically determined crown projection areas vs. GIS-determined canopy areas may explain the different dry matter estimates. In principle the GIS-determined canopy area should be smaller than the computed crown projection area (Fig. 7). The GIS-determined canopy area of the sample shrub in Fig. 7 was always the same, whereas the sum of the allometrically computed crown projection

Table 5. Time requirement for biomass estimates of *Alhagi sparsifolia* at Qira oasis, NW China.

Ground based allometric estimate		GIS-based aerial photography	
Establishment of the regression equation			
Establishment of sample squares	1 d	Establishment of sample squares	1 d
Measurement of shrub dimensions (473 shrubs)	2 d	Measurement of shrub dimensions (473 shrubs)	2 d
Sample preparation, data evaluation	2 d	Aerial photograph, digititizing of the photograph, image classification	1 d
		Developing of an algorithm to separate clumps, data processing	16 d
Total time required	5 d	Total time required	20 d
Application on a field of size 1 ha			
Measurement of shrub dimensions[1]	16 d	Taking of two aerial photographs,	
Data evaluation	1 d	establishment of ground control points	0.5 d
		Digitizing, data processing	1 d
Total time required	17 d	Total time required	1.5 d

[1] assuming a density of 6400 shrubs/ ha and manual measurements of 800 shrubs (2 man days)$^{-1}$

Table 6. Comparison of ground-based and GIS-based detected above-ground biomass (AGB) and canopy areas of sample shrubs of *Alhagi sparsifolia* at Qira oasis, NW China.

	Allometric AGB estimate (kg)	GIS-based AGB estimate linear (kg)	GIS-based AGB estimate non-linear (kg)	Crown projection area (m^2)[1]	Canopy area detected by GIS (m^2)	Mean shrub crown projection area (m^2)	Biomass density[2] (kg.m^{-2})
50 shrubs harvested in 2000	12.6	13.4	12.2	36.7	18.2	0.65	0.34
Shrubs in 20 sample squares	52.1	85.6	73.3	161.2	115.8	0.33	0.32
Shrubs in eastern 10 sample squares	26.0	47.1	40.0	81.2	63.7	0.28	0.32
Shrubs in western 10 sample squares	26.1	38.5	33.3	80.0	52.1	0.41	0.33

[1] computed as an ellipse using measured length and width of the shrubs; [2] related to crown projection area

areas depended on the number of shrubs in the clump (Fig. 7b-d).

Assuming that the ratio between biomass density and crown projection area remained similar (Table 6), it is possible to explain why the biomass density related to the GIS-detected canopy area should be smaller in shrub clumps and densely vegetated areas compared with solitary shrubs. This also explains the overestimation of biomass in the sample squares determined with the GIS-approach and the robustness of the allometric approach. Based on these findings the use of non-linear regression equations in the GIS-based approach is recommended as it takes into account that the biomass density in shrub clumps is lower than in single shrubs. The close agreement between the non-linear GIS-based estimate and the allometric estimate at the field level indicated, that errors of the GIS-based estimate should substantially decrease with increasing field size.

Strong edge effects for the AGB determination in sample squares may be expected because the sample square size of 4 m × 4 m was relatively small in comparison to the individual shrub projection area. These edge effects affected the GIS-based and allometric approaches differently (see Material and Methods section).

The time requirement for the GIS-based AGB estimation depends much on the height from which the aerial photograph is taken and the corresponding quality of the image whereby image quality is a function of resolution (scale) and shading. The useful image resolution also depends on the optical properties of camera equipment, film material and film-scanning device. Therefore larger camera heights may be compensated up to a certain limit (film grain resolution) by a higher scanning resolution. Taking photographs from a higher altitude would allow to keep the scale constant to avoid effects like changing pixel variances (Cao & Lam 1997) and clumping (Laurini & Thompson 1999). Shading depends on sun elevation and thus the length of the daily monitoring period around midday.

Further research may be needed to optimize this technique for application in larger areas of interest. As such the methodology should work particularly well in environments with sparse vegetation coverage and dominated by a single photo-synthetically active plant species.

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