BIOMASS ESTIMATION FOR LAND USE MANAGEMENT AND FIRE MANAGEMENT USING LANDSAT-TM AND -ETM+

With 10 figures, 3 tables and 3 photos

TANJA KRAUS and CYRUS SAMIMI

Zusammenfassung: Biomassebestimmung mit Hilfe von Landsat-TM und -ETM+ für Landnutzungsplanung und für Feuermanagement

Beweidung und Feuer sind wichtige Umweltfaktoren in den Savannenökosystemen des südlichen Afrika. Im Weideland aber auch in Nationalparks führt dabei zu hoher Beweidungsdruck zur Degradation der Vegetation und des Bodens. Unzureichendes Feuermanagement kann ebenfalls die natürliche Artenzusammensetzung verändern und zudem den Bodenhaushalt negativ beeinflussen. Für Planungszwecke ist deshalb eine flächenhafte Kenntnis der Biomasseverhältnisse unabdingbar, die z. B. mit hochauflösenden Satellitensystemen gewonnen werden kann. In der vorliegenden Studie wurden drei Testgebiete im südlichen Afrika untersucht. Ein Gebiet liegt im Gutu Distrikt in Zimbabwe. Die dortigen Communal Lands sind durch hohen Bevölkerungsdruck stark degradiert. Die anderen Gebiete befinden sich mit dem Krüger Nationalpark und dem Madikwe Wildschutzgebiet in der Republik Südafrika. Somit ist eine ökologische Spanne von stark degradierten bis wenig gestörten Savannenökosystemen abgedeckt. Als Satellitendaten standen Landsat–5 (TM) und Landsat–7 (ETM+) zur Verfügung. Nach der Kalibrierung der beiden Systeme aufeinander wurden Strahlung und Reflexion aus den Originaldaten abgeleitet. Darüber hinaus wurden aus den Grauwerten, der Strahlung und der Reflexion zahlreiche Indices errechnet, extrahiert, für jede Testfläche gemittelt und anschließend mit den im Feld erhobenen Biomassewerten statistisch in Beziehung gesetzt. Dabei ergaben sich signifikante Zusammenhänge mit den Ratios Strahlung/Reflexion der Kanäle 7/1 und 2/1 sowie dem Tasselled Cap Wetness Index und der Grasbiomasse. Die Summe der Grasbiomasse und der Blattbiomasse der Bäume und Sträucher korreliert ebenfalls mit den Ratios 2/1 und 7/1. Zusätzlich ist hier der Tasselled Cap Brightness Index zur Quantifizierung gut geeignet. Die Holz- und Gesamtbiomasse ergab hingegen keine signifikanten Zusammenhänge mit den Satellitendaten. Die Anwendung und Überprüfung der Regressionsmodelle im Gutu Distrikt zeigt, dass die Berechnung der Biomasse aus Satellitendaten im Genauigkeitsbereich der Geländebestimmung liegen. Somit stehen Modelle zur Quantifizierung der Gras- und Blattbiomasse auf einer regionalen Maßstabsebene zur Verfügung.

Summary: Grazing and fire are major factors influencing the savanna ecosystems of Southern Africa. In both grazing and conservation areas overgrazing is an important reason for degradation of vegetation and soil. Insufficient fire management can cause a change in the species composition and may influence the soil negatively. For adequate planning purposes the knowledge of available biomass is indispensable. High-resolution satellite systems can provide such knowledge on a large scale. Three study areas in Southern Africa contributed to this present survey. Gutu District is situated in Zimbabwe. In its Communal Lands a high population density leads to severe degradation of vegetation and soil. The South African test sites are located in Kruger National Park and Madikwe Game Reserve. Therefore a wide ecological range from highly degraded to slightly disturbed savanna ecosystems is included. Satellite images of both Landsat–5 (TM) and Landsat–7 (ETM+) were applied. After cross-calibration of the two different satellite systems, radiance and reflectance were derived from the raw data. Furthermore, digital numbers, radiance and reflectance were used to calculate different indices. These indices were then extracted and averaged for each test site and statistically analysed together with the different types of above-ground biomass. Significant correlations resulted from ratios of radiance and reflectance of bands 2 and 1 as well as bands 7 and 1 with grass biomass and total foliage biomass. In addition the Tasselled Cap Wetness Index is very useful to quantify grass biomass and the Brightness Index to calculate total foliage biomass. In contrary no significant correlation could be detected for woody biomass and total above-ground phytomass. The application of the regression models in the Gutu district indicated that grass biomass calculated from satellite data is within the range of the biomass measured in the field. Thus models for predicting grass and total foliage biomass are available on a regional scale.

1 Introduction and background

The vegetation in Southern Africa varies from low tropical rain forest in the north to desert along the Namibian coast and to Fynbos at the south-western tip of the Republic of South Africa. However, the largest part of the region is dominated by various kinds of savannas (WHITE 1983). These ecosystems include different types of miombo woodland, a mainly deciduous woodland characterised by the genera *Brachystegia, Julbernardia* and *Isoberlina,* several kinds of grasslands, Acacia woodland and mopane woodland (CAMP-

BELL et al. 1996). Southwards the savanna ecosystems change to subtropical grassland in South Africa. In the west and south-west of South Africa and Namibia the Nama-Karoo ecozone marks the limit of their distribution. The occurrence of miombo in southern parts of the Democratic Republic of Congo (DRC) and in Tanzania could be used to ecologically demarcate the Southern African subregion in the north.

The ecological situation and the historical background are the reasons for human activities which result in impacts on the ecosystems and their management. In large parts, grazing is the primary form of agricultural land use and about two-thirds of the region are suitable for grazing only (CHENJE a. JOHNSON 1994). However, the first nature conservation areas were established in the late 19th century and extended by the colonial powers in the early 20th century. Today 15.66 % of Southern Africa are designated as protected areas (Southern African Development Community without DRC, Madagascar and Mauritius), reaching an estimated 237.000 sq km in Tanzania and 39.0 % of the total land area in Botswana (CHENJE a. JOHNSON 1994).

As a consequence of the present land use overgrazing has become the main ecological problem of many regions. Certainly it can be observed in all types of land-tenure, but mainly occurs in highly populated regions. These areas, such as the Communal Lands, the former native reserves during colonialism in Zimbabwe or the Homelands during apartheid in South Africa and Namibia, suffer from this development (CHENJE a. JOHNSON 1994, WHITLOW a. CAMPBELL 1989). In addition to vegetation and soil degradation overgrazing is the essential factor accounted for bush encroachment particularly in Botswana, South Africa and Namibia. In nature conservation areas high wildlife densities cause the same processes (ECKHARDT et al. 2000). Therefore the containing or even the reversal of these developments is a main challenge in the planning of land use.

Fire, which is a natural part in most Southern African ecosystems, still plays a major role in grazing and conservation areas. In the latter and on large commercial farms it has always been controlled or even suppressed, which has lead to a change in the natural species composition. Additionally contributing to the danger of severe fires is the accumulation of litter (DU PLESSIS 1997, TROLLOPE et al. 1996). In other regions very short fire frequencies entail a reduction of soil cover and a change in the species composition, as HUNTLEY (1982) states specially for dry savannas. The importance of fire and fire management as well as the need for a better understanding of fire and its interactions within ecosystems is a major goal of research initiatives such as SAFARI 1992 and SAFARI 2000.

For proper management of grazing and fire it is essential to have knowledge of the available biomass. The grazing capacity depends on the quality and the quantity of the palatable vegetation. Grazers feed on grasses and herbs, browsers on reachable leaves of bushes and trees. The same parts of above-ground biomass are determining factors for fuel load and therefore for the occurrence and the characteristics of fires (SHEA et al. 1996). Many fires occur during the winter months, when the fuel load mainly consists of dry grass and dry foliage of bushes and trees at low heights, therefore these studies took place during the dry season. For planning purposes spatial information about the portion of the total above-ground biomass is crucial.

2 Use of satellite imagery for biomass estimations

Since satellite data have been available, the direct quantification of biomass and other vegetation parameters have become a focus of research. Nevertheless it is still of minor importance compared to other aspects of remote sensing, as for example classification methods. In general more effort has been made to study agricultural plants than non-agricultural vegetation (e.g. ASRAR et al. 1985, DUSEK et al. 1985, WIEGAND et al. 1992). The quantification of vegetation parameters in African ecosystems can be divided into two main approaches. The first focuses on large scale analyses using NOAA-AVHRR data (e.g. MENZ 1994, TUCKER et al. 1983, TUCKER et al. 1985), whereas the second one is based on measurements with spectroradiometers and high resolution images like Landsat-MSS, -TM, -ETM+ and SPOT (e.g. EVERITT et al. 1989, FRANKLIN a. HIERNAUX 1991, FRANKLIN a. STRAHLER 1988, HELLDÉN a. OLSSON 1982, OLSSON 1984).

3 Study areas

The results of two projects were combined: the data from Zimbabwe were collected during a study about grazing capacity, whereas the South African data were gathered during field studies under SAFARI 2000. The Zimbabwean study area is located in parts of the Communal Lands in Gutu District, about 150 km south-east of Harare (Fig. 1). It is a typical Zimbabwean Communal Land with climatic conditions that according to the agro-ecological classification of VINCENT a. THOMAS (1962) are only suitable for extensive beef production or semi-extensive livestock production, in small

Fig. 1: Regional map with location of the study areas
Übersichtskarte mit Lage der Untersuchungsgebiete

Photo 1: Test site in Gutu District (Zimbabwe) showing degradation due to overgrazing
Die Testfläche im Gutu Distrikt (Zimbabwe) zeigt starke Degradationserscheinungen aufgrund hohen Beweidungsdrucks

Photo 2: Test site in Kruger National Park (South Africa), the situation shows dense grass cover with low tree and shrub densities

Die Testfläche im Krüger National Park (Südafrika) ist geprägt durch eine dichte Grasbedeckung mit einer geringen Baum- und Strauchdichte

parts for semi-intensive farming. The high and steady growing population has drastically changed the natural vegetation (Samimi 2000). Despite the agro-ecological classification the main farming activities are cultivation and livestock production. Thus livestock densities exceed the carrying capacity of the region, which results in a degraded status of the vegetation. Remains of woodland only occur in small areas of the Communal Lands in Gutu District. The main non-agricultural vegetation consists of grassland, wooded grassland, open woodland and shrubland. The woody vegetation is often characterised by large numbers of *Dichrostachys cinerea* and different species of *Acacia*. Many of the occurring grass species indicate high grazing pressure. In general the pastures have a low amount of biomass (Photo 1).

Kruger National Park is situated in the north-eastern part of South Africa, close to Zimbabwe in the north and Mozambique in the east (Fig. 1). Established in 1896, it forms one of the oldest nature conservation areas in South Africa. For the purpose of simulating and thereby better understanding natural fire regimes,

Photo 3: Test site in Madikwe Game Reserve (South Africa), having a dense grass cover. The shrub density is slightly higher than the tree density

Die Testfläche im Madikwe Game Reserve (Südafrika) hat eine dichte Grasdecke, wobei die Buschdichte höher als die Baumdichte ist

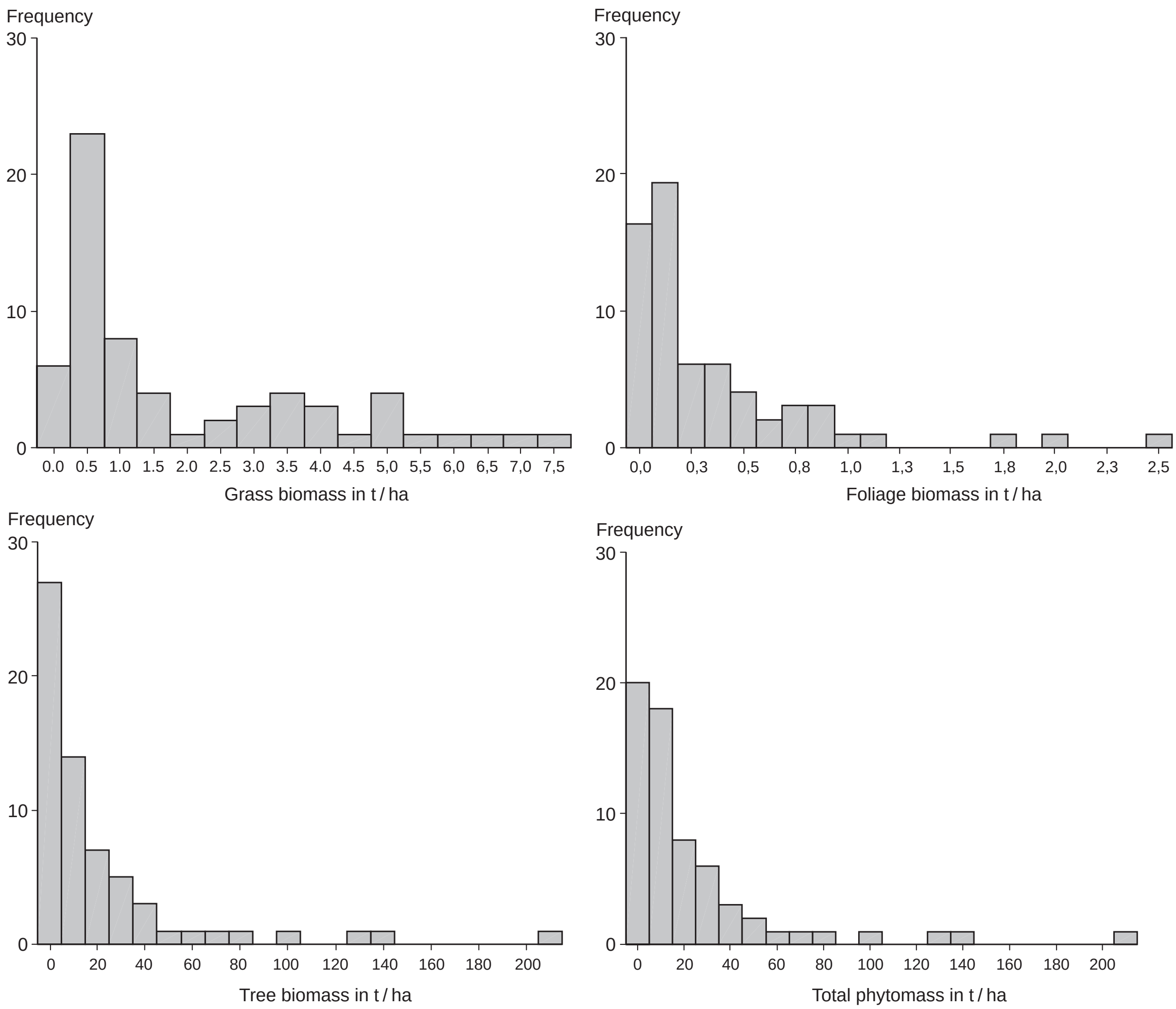

Fig. 2: Frequency distribution of grass biomass, foliage biomass, tree biomass and total above-ground phytomass
Häufigkeitsverteilung von Grasbiomasse, Blattbiomasse, Baumbiomasse und oberirdischer Phytomasse

a systematic burning program was initiated in 1954. It currently involves 456 burning plots in 88 management units. The burning plots used in this study are mainly situated in the southern region of the park, in the vicinity of Skukuza, Pretoriuskop and Satara rest camps. All test sites are located in arid savanna regions and are broadly classified as undifferentiated woodland (WHITE 1983) (Photo 2).

Madikwe Game Reserve is situated in South Africa's North Western Province on the border to Botswana (Fig. 1). The Park lies in a transition zone from undifferentiated woodland to Acacia deciduous bushland and wooded grassland including mosaics of communities dominated by *Acacia spec.* and broad-leaved trees (WHITE 1983) (Photo 3). All of the test sites are located in the north-eastern part of the Game Reserve and are, as the sites in Kruger National Park, characterised by relatively high amounts of phytomass.

4 *Methodology*

4.1 Field work

In order to quantify total above-ground phytomass, data samples were collected on 64 test sites in three study areas during the dry season: 42 in Gutu District, 15 in Kruger National Park and 7 in Madikwe Game Reserve. In this study phytomass and biomass are used as dry mass and defined as follows:

Table 1: Descriptive statistical analysis of the different biomass classes
Deskriptive statistische Analyse der verschiedenen Biomasseklassen

	study site	grass biomass in t/ha	foliage biomass in t/ha	total foliage biomass in t/ha	tree biomass in t/ha	phytomass in t/ha
Gutu	median	0.60	0.26	1.10	7.34	771
	min	0.14	0.01	0.17	0.09	0.39
	max	1.86	2.45	2.64	208.54	20877
	25% quartile	0.38	0.08	0.73	1.53	2.81
	75% quartile	0.98	0.67	1.52	31.25	3190
	N	42	42	42	42	42
Madikwe	median	4.57	0.07	4.64	3.60	1058
	min	2.75	0.00	2.75	0.00	2.83
	max	6.98	0.55	7.07	26.83	29.96
	25% quartile	3.12	0.00	3.60	0.08	4.81
	75% quartile	5.65	0.36	6.02	8.99	14.64
	N	7	7	7	7	7
Kruger	median	4.02	0.10	4.11	13.11	1691
	min	2.65	0.00	2.91	0.38	4.06
	max	7.34	1.06	8.40	65.52	6818
	25% quartile	3.65	0.01	3.65	3.36	707
	75% quartile	5.07	0.19	5.21	24.65	2949
	N	15	15	15	15	15
total	median	98	0.15	155	7.59	1014
	min	14	0.00	0.17	0.00	39
	max	7.34	2.45	840	208.54	20877
	25% quartile	0.49	0.05	90	169	360
	75% quartile	3.63	0.48	367	26.29	2984
	N	64	64	64	64	64

– grass biomass includes the mass of grass and herbaceous species and litter,
– foliage biomass comprising of leaves of bushes and trees,
– tree biomass is the sum of foliage and woody biomass,
– total foliage biomass consists of grass biomass and foliage biomass,
– total phytomass is the mass of the whole above-ground vegetation.

4.1.1 Grass biomass

In South Africa the disc pasture meter was used to estimate the grass biomass. In addition to fast sampling, this method provides also rather accurate results, especially when using a calibration based on clippings developed by Trollope a. Potgieter (1986). One hundred readings located on a stratified random basis were recorded per plot and helped to calculate grass biomass in t/ha. In Gutu District the 10-point-frame (point-intercept-method) as described by Mueller-Dombois a. Ellenberg (1974) was deemed to be more suitable to the aims of the study undertaken there, as it distinguishes between litter and green biomass and is more appropriate for sparse grass cover. The 10-point-frame was tested and calibrated in Gutu based on 240 clippings. Then the assessment of the biomass for each test site was carried out by a representative number of quadrats. The biomass was calculated as a mean value for each test site.

4.1.2 Foliage and woody biomass

In Kruger National Park and Madikwe Game Reserve three sample plots (10 x 10 m) were chosen randomly on each 120 m x 120 m test site. All shrubs and trees on these plots were measured in terms of tree/shrub height, basal stem circumference and number of stems. After that woody biomass as well as foliage biomass and tree biomass (dry matter) were calculated by using regression equations developed by Rutherford

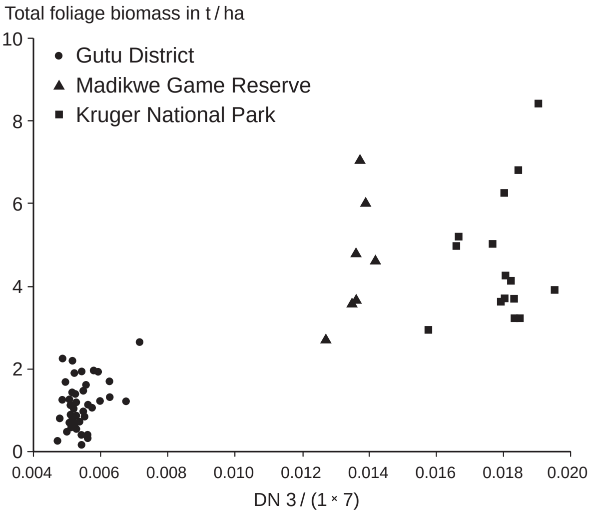

Fig. 3: Scatter plot of total foliage biomass and spectral index DN 3/(1*7); because of the separation into two groups indices of this type were not included in further considerations

Streudiagramm der Blatt- und Grasbiomasse mit dem spektralen Index DN 3/(1*7); wegen der Trennung in zwei Gruppen wurden Indizes dieser Art in weitere Überlegungen nicht einbezogen

(1982) for combined species in Southern Africa. These equations are well evaluated in the region for different species and habitats. On the test sites in Gutu tree and bush variables were measured along spatially defined transects (BAAS 1993). The calculation of biomass was done by regression equations as already described and was then projected from the transects to the whole test site.

4.2 Satellite data

Images of both Landsat–5 (TM) and Landsat–7 (ETM+) were processed in the study. In Gutu Landsat–5 scene 169/74 (12/10/1998), in Madikwe Game Reserve and in Kruger Park Landsat–7 scenes 172/77 (11/08/2000) and 178/77 (12/06/2000) came into use. The acquisition dates of the Landsat images were close to the dates of the field work due to the fact that only then it was possible to compare the field data with the satellite data. Due to the ageing of Landsat–5 and different pre-flight calibrations of the sensors the need of cross-calibrating the satellites was evident. TEILLET et al. (2001) used tandem-flights of Landsat–5 and Landsat–7 for a radiometric cross-calibration of the two systems. The aim of the cross-calibration is to adjust Landsat–5 to Landsat–7 and hence get consistent data from both satellites. The digital numbers (DNs) of the Landsat–5 image for Gutu were adjusted to Landsat–7 for the South African sites by the gains and biases published by TEILLET et al. (2001). These calibrated DNs are then directly comparable to the DNs of Landsat–7. The DNs were furthermore transferred into radiance (L). As the field work took place at different times of the year and the geographic positions of the study areas were different, the DNs were also transferred into reflectance (ρ).

In the next step DNs, radiance and reflectance of Landsat Bands 1–5 and 7 were used to calculate different indices (DUSEK et al. 1985, GARDNER 1985, HILDEBRANDT 1996). These indices either consist of individual bands or band combinations in the form of ratios, ratios of differences divided by sums (normalized difference) or linear combinations. Furthermore Tasselled Cap Indices derived from HUANG (2001) completed the total amount of 134 indices. The indices were then extracted and averaged for each test site and statistically analysed together with the different types of above-ground biomass estimations.

5 Results

Histograms and statistics clearly point out the differences between the test sites (Fig. 2, Tab. 1). In Kruger National Park and in Madikwe Game Reserve the grass biomass is significantly higher than in Gutu whereas foliage biomass is lower. This causes a certain skewness of the frequency distribution. In contrary, tree biomass and total above-ground biomass in Gutu top the ones on the South African sites, but the differences are not significant. Since the samples are not normally distributed, the differences of the means were tested with the U-test (MANN-WHITNEY). Despite the high variance only a few samples of foliage biomass, tree biomass and

Table 2: Regression equations and coefficients of determination for grass biomass on certain spectral indices (y = grass in t/ha; x = spectral index; N = 64)

Regressionsgleichungen und Bestimmtheitsmaße für Grasbiomasse mit bestimmten spektralen Indizes (y = Grasbiomasse in t/ha; x = spektraler Index; N = 64)

index	regression equation	r^2
L 2/1	$y = (-4.53 + 5.22/x)^2$	0.83
ρ 2/1	$y = (-4.53 + 5.58/x)^2$	0.83
L 7/1	$y = (2.76 - 15.79x)^2$	0.79
ρ 7/1	$y = (2.76 - 0.65x)^2$	0.79
Tasselled Cap Wetness (ρ)	$y = (3.02 + 5.97x)^2$	0.78
ρ (2*5)/3	$y = -1.74 + 0.30/x^2$	0.76

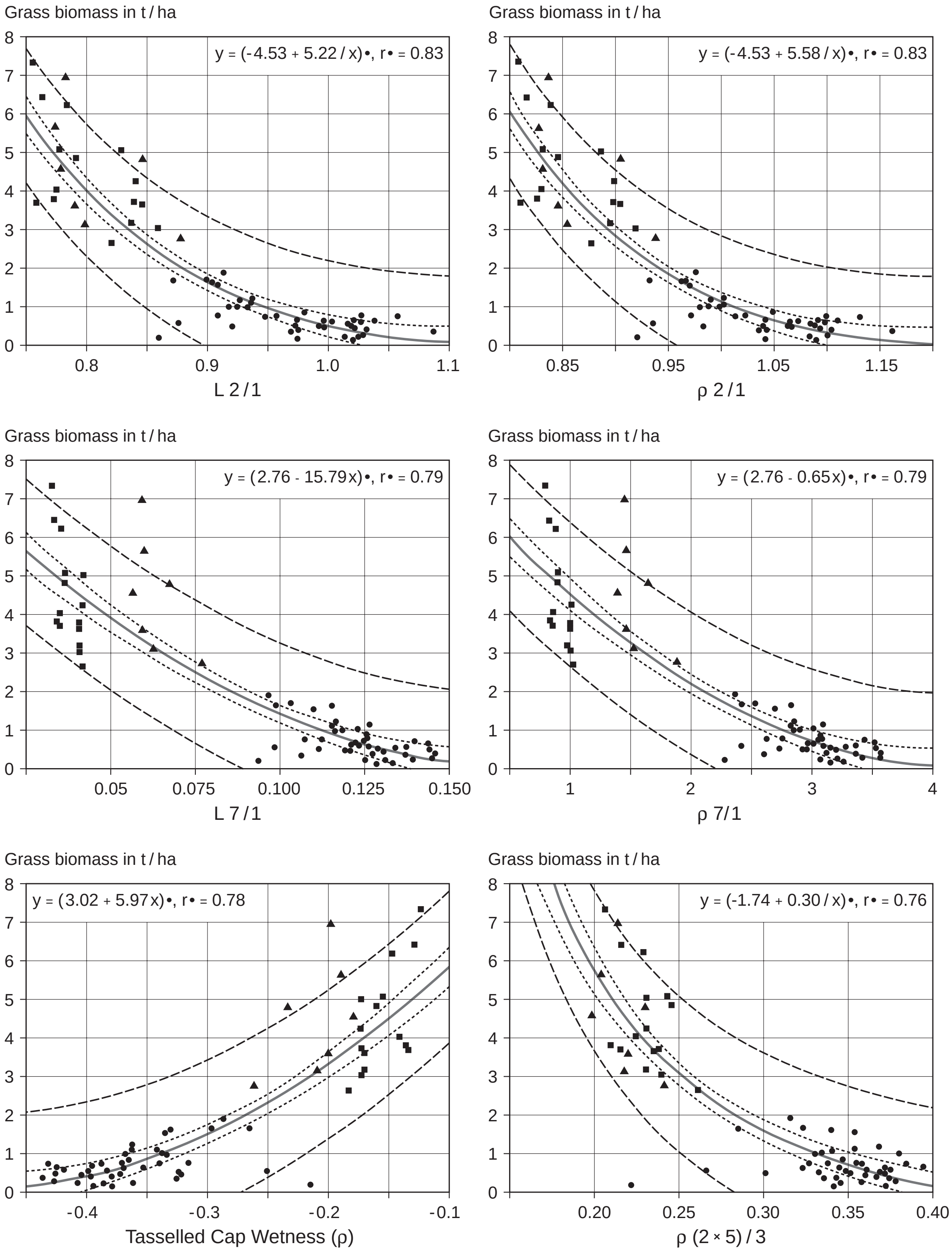

Fig. 4: Regression of grass biomass (dry matter) on the best correlating spectral indices. The figure shows the regression equations with the 95 % confidence interval and the 95 % prediction interval (● = Gutu District, ▲ = Madikwe Game Reserve, ■ = Kruger National Park)

Regressionsdiagramme der Grasbiomasse (Trockengewicht) mit den sechs bestkorrelierenden spektralen Indizes. Die Abbildung zeigt die Regressionskurven mit dem 95 %-Konfidenz- und dem 95 %-Vorhersageintervall

Table 3: Regression equations and coefficients of determination for total foliage biomass on certain spectral indices (y = total foliage biomass in t/ha; x = spectral index; N = 64)

Regressionsgleichungen und Bestimmtheitsmaße für die gesamte Blatt- und Grasbiomasse mit bestimmten spektralen Indizes (y = gesamte Blatt- und Grasbiomasse in t/ha; x = spektraler Index; N = 64)

index	regression equation	r^2
Tasselled Cap Brightness (L)	$y = (-0.45 + 168.6/x)^2$	0.82
L 2/1	$y = (-3.66 + 4.59/x)^2$	0.81
ρ 2/1	$y = (-3.66 + 4.91/x)^2$	0.81
ρ (2*5)/3	$y = -1.26 + 0.29/x^2$	0.76
L 7/1	$y = (2.73 - 13.66x)^2$	0.75
ρ 7/1	$y = (2.73 - 0.56x)^2$	0.75

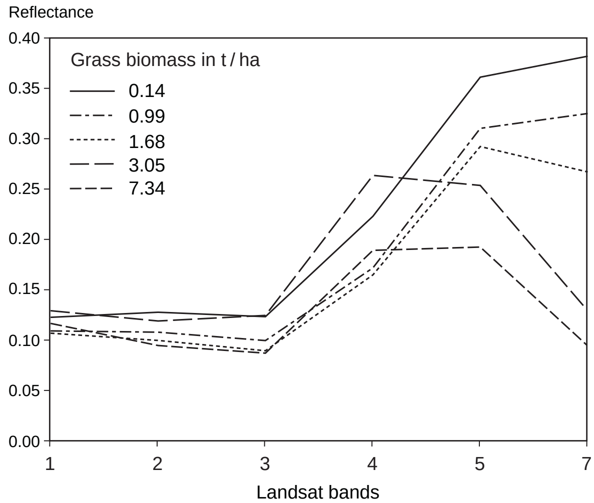

Fig. 5: Spectral reflectance curves for five different grass biomass values

Reflexionsdiagramm für fünf verschiedene Grasbiomassewerte

total phytomass can be classified as outliers. One of these locations is situated in Kruger National Park whereas the other test sites are in Gutu. These sites are either classified as dense woodland or characterised by the occurrence of the tree species like *Kigelia africana* or *Ficus spec*. With the samplings being part of independent studies, the design of sampling in different areas was not specially planned. That is why the test sites might not be representative for all South African savanna bioms, but nevertheless they cover a wide spectrum of biomass values from very low to high and different soil types.

Correlation analyses indicate that certain indices were highly correlated with biomass ($p < 0.001$). In general grass biomass correlated best, followed by total foliage biomass. Woody biomass showed no significant correlation, probably because of its minor influence on the reflectance compared to total foliage biomass and grass biomass. As woody biomass has a big influence on total above-ground phytomass, no significant correlation could be detected for the latter. Regression analyses for the highly correlated indices result in nonlinear relations and are therefore described by nonlinear models.

The correlation of grass biomass with vegetation indices results in good outcomes in quite a few cases. Altogether 64 indices yielded a correlation coefficient of 0.8 or higher. Especially combinations with ETM+ Bands 1, 2, 5 and 7 worked out very well. However, scatter plots of indices and biomass revealed that not all indices had an equal distribution. Mainly the sites in Gutu are separated from the South African sites. Figure 3 shows an example with the Gutu sites being concentrated in the lower left part of the scatter plot. Therefore indices with an unequal distribution were not included in the further considerations. It is also evident that indices calculated from DNs correlate less than the indices calculated from L and ρ. Table 2 and Figure 4 show a selection of the best fitting equations.

Simple regression models that combine radiance or reflectance of bands 2 and 1 or bands 7 and 1 fit very well. Often being used for green biomass, equations like the NDVI however, do not correlate with dry grass biomass. The good suitability of band 1 and band 7 becomes obvious by examining the reflectance curve for the Landsat bands (Fig. 5). Five samples with different grass biomass values represent the trend of the reflectance curves. Concerning band 1 the reflectance values of the different biomass amounts showed no significant differentiation. In contrast the reflectance diverges widely when regarding band 7. A similar observation for Landsat band 7 was published by RINGROSE et al. (1997) for the classification of vegetation in Botswana. In figure 5 the applicability of band 2 is not obvious. But if band 1 and band 2 are examined closely it appears that the reflectance of band 2 decreases significantly with increasing biomass. The Tasselled Cap Wetness Index (ρ) is again strongly dependent on Landsat band 7 and therefore the same relations apply as described above.

Concerning total foliage biomass (grass biomass and foliage biomass) Table 3 and Figure 6 show similar results to those for the grass biomass. Again ratios of band 2 and band 7 (L and ρ) show good correlations. Yet the best fit is performed by the Tasselled Cap Brightness Index calculated with radiance. The Bright-

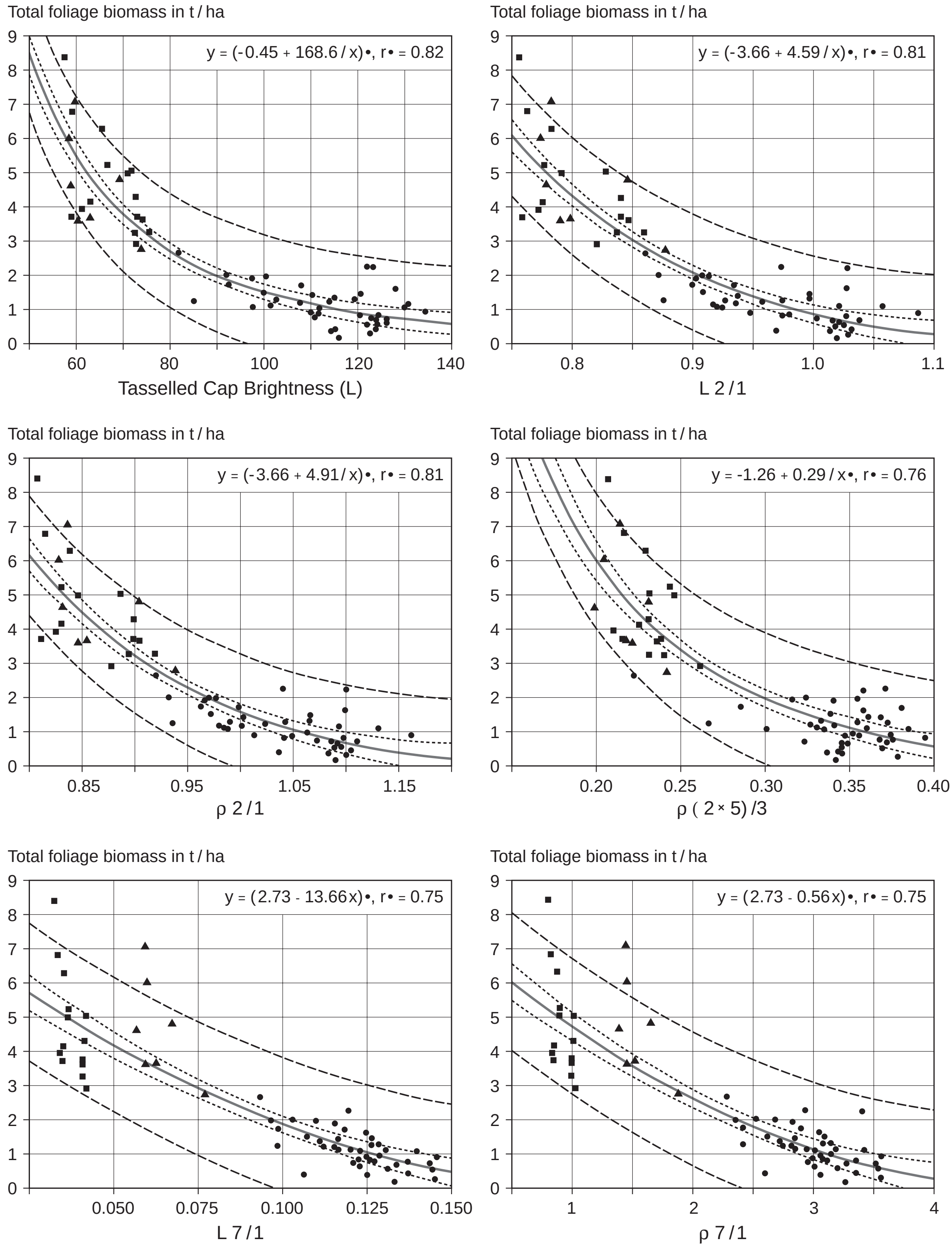

Fig. 6: Regression of total foliage biomass (dry matter) on the best correlating spectral indices. The figure shows the regression equation with the 95 % confidence interval and the 95 % prediction interval (● = Gutu District, ▲ = Madikwe Game Reserve, ■ = Kruger National Park)

Regressionsdiagramme der Blatt- und Grasbiomasse (Trockengewicht) mit den sechs bestkorrelierenden spektralen Indizes. Die Abbildung zeigt die Regressionskurven mit dem 95 %-Konfidenz- und dem 95 %-Vorhersageintervall

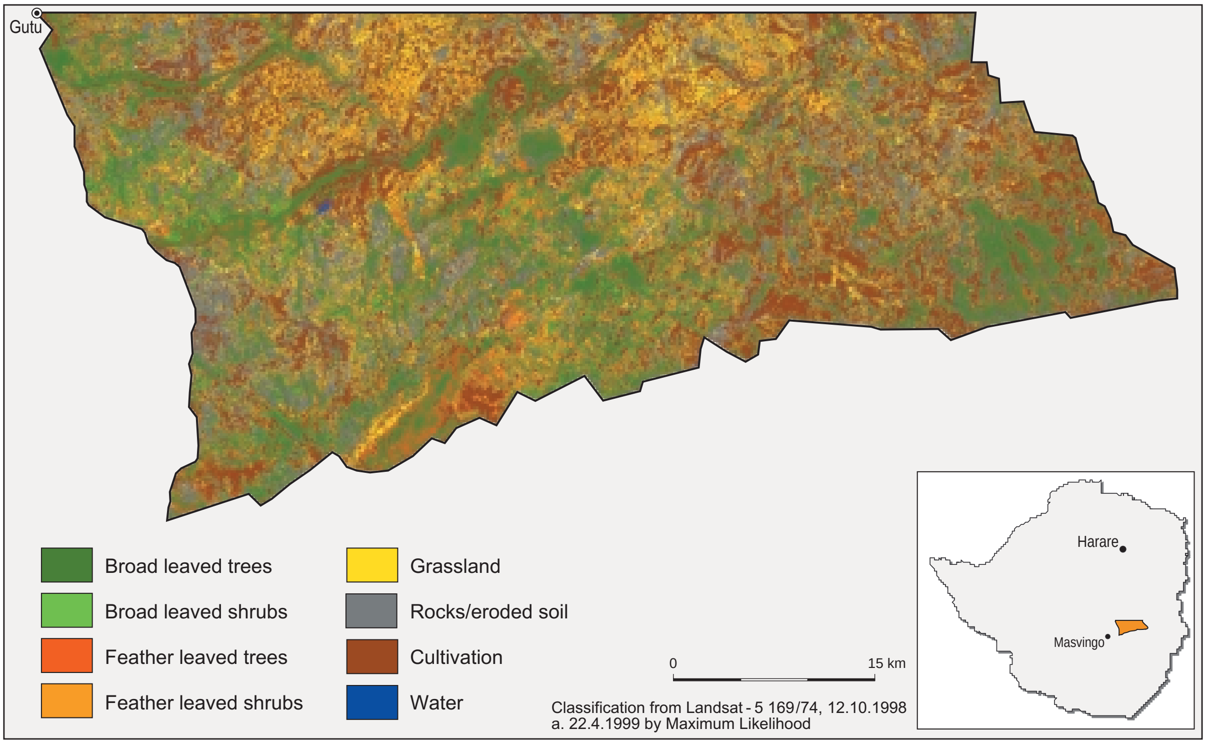

Fig. 7: Vegetation and land use classes in the Gutu study area derived from Landsat–5 (169/74, 12.10.1998, 22.4.1999) by Maximum Likelihood

Vegetations- und Landnutzungsklassifikation im Untersuchungsgebiet Gutu ermittelt aus Landsat–5 (169/74, 12.10.1998, 22.4.1999) mit dem Maximum-Likelihood-Klassifizierer

ness Index is strongly dependent on Landsat band 4 followed by band 1 and band 2. This result might be attributed to the fact that leaves of trees and shrubs are at least partly green also during the dry season. The Brightness Index emphasises band 1, band 2 and band 4 and might therefore reflect the fact that the total foliage biomass consists of green leaves and dry grass. As for the grass biomass differences in soil reflectance seem to have no influence on the correlations. The tree biomass and the total biomass show no significant correlation with any of the tested indices. The confidence and prediction intervals in the regression diagrams of figure 4 and figure 6 show the range of predicting biomass with the regression models on a 95%-level. When using the models for planning purposes it is recommended to keep the prediction intervals in mind.

6 Application of the grass biomass model to the Gutu study area

With the discussed regression equations it is possible to derive biomass values for larger areas from satellite images. Before calculating the grass biomass it is necessary to mask out areas with high portions of woody vegetation cover. These masks can for instance be derived from classified images (Fig. 7). In this example the four woody classes were excluded from the calculations. The class "cultivation" was included because at the end of the dry season most of the fields are fallow and often grassy vegetation developed. The class "rock/eroded soil" also contains areas with sparse grass cover. When applying the regression equations to the masked image a map is produced which gives the calculated amount of grass biomass (Fig. 8).

The grass biomass calculated from satellite data correlate significantly ($p < 0.0001$) with the measured grass biomass (Fig. 9). Despite the fact that r^2 for the ratio of band 7 and band 1 is slightly lower than for band 2 and 1 (Tab. 2, Fig. 4), the ratio ρ 7/1 produced better results. Figure 10 shows the range of the grass biomass on the test sites and the variance of the calculated biomass for the test sites. It is obvious that both methods contain an uncertainty. For this reason, to get more accurate values in the field, it would be necessary to increase the number of test sites and additionally increase the number of sampling quadrats on the test sites or alternatively, enlarge them. Therefore measuring biomass for large areas is either very time-consuming

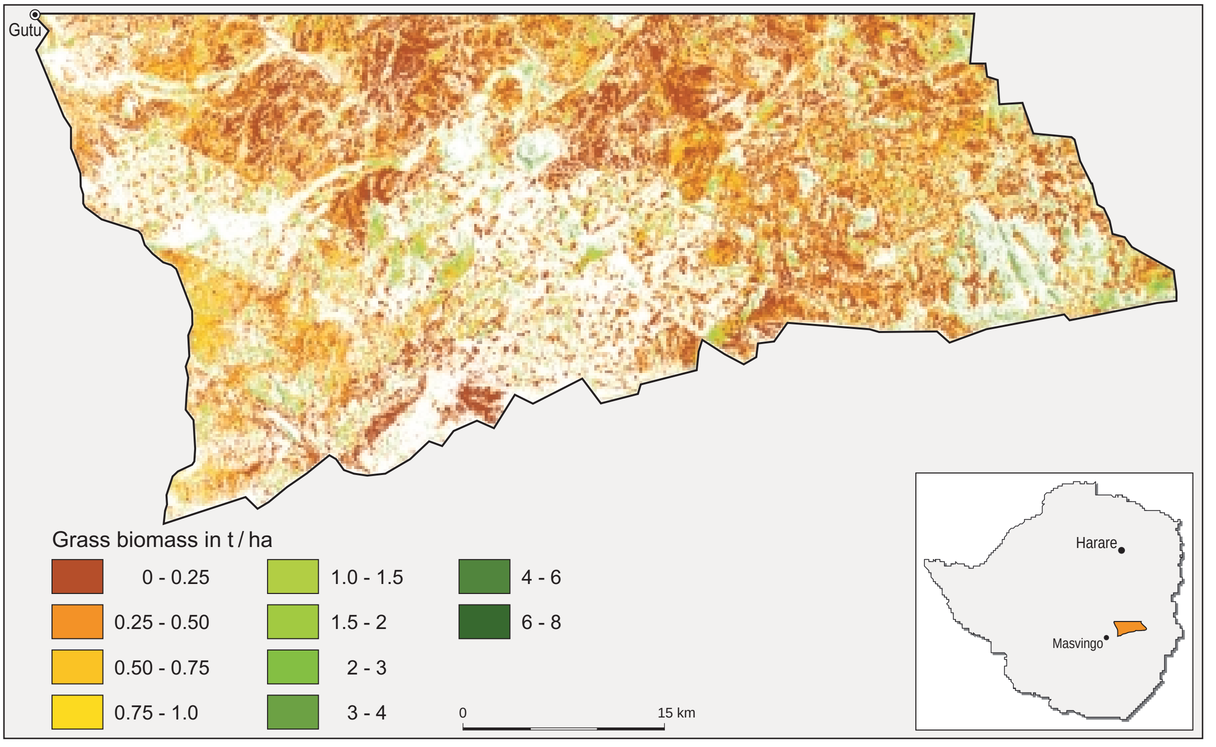

Fig. 8: Calculated grass biomass for the Gutu study area. Calculation with Landsat–5 (169/74, 12.10.1998) using the regression equation for the ratio ρ 7/1

Aus Landsat–5 (169/74, 12.10.1998) mit der Regressionsgleichung für das Ratio ρ 7/1 errechnete Grasbiomasse im Untersuchungsgebiet Gutu

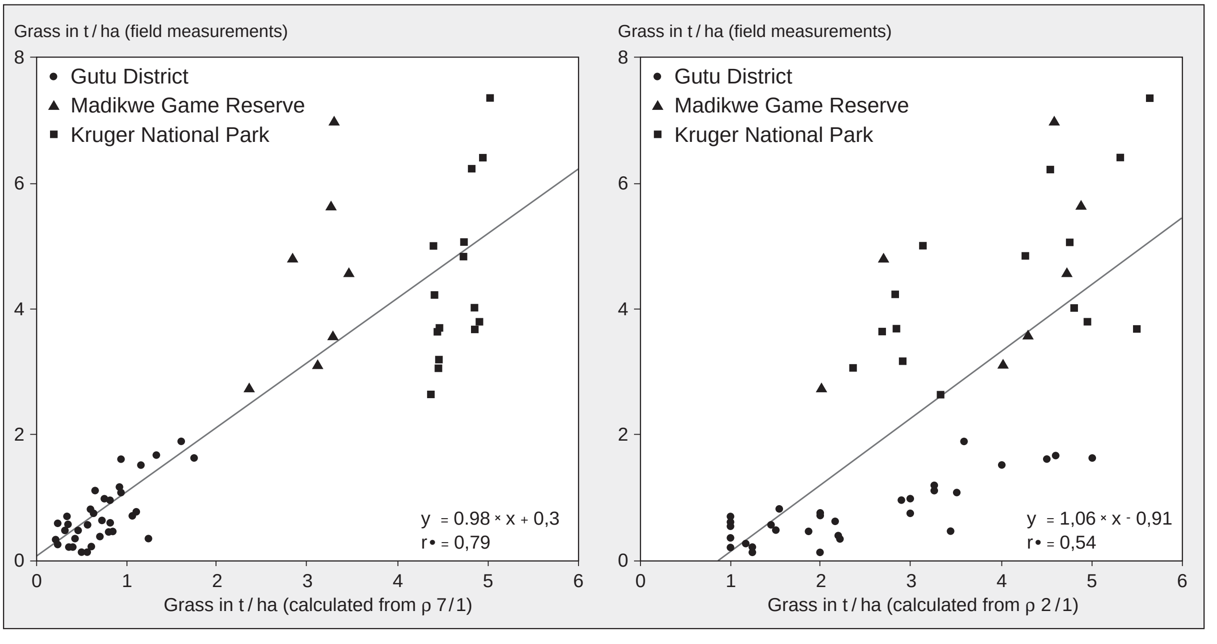

Fig. 9: Correlation of calculated and measured grass biomass

Korrelation der errechneten und gemessenen Grasbiomasse

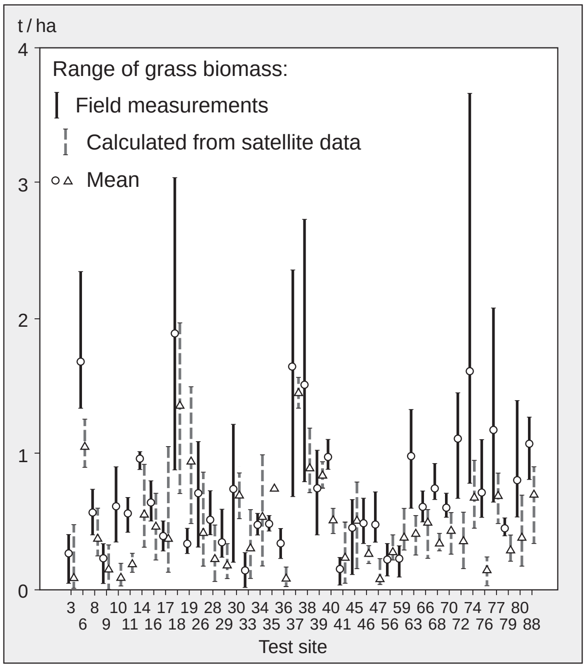

Fig. 10: Ranges of grass biomass measured in the field and calculated from Landsat–5 in the Gutu study area

Wertebereiche der im Gelände erhobenen und der aus Landsat–5 errechneten Grasbiomasse im Untersuchungsgebiet Gutu

when exact results are needed, or it is an estimate. As a result, the estimation from satellite images is an adequate tool for a quick assessment of biomass for larger areas.

7 *Concluding remarks*

The presented results show that high resolution satellite images can be used to predict both dry grass biomass and the sum of dry grass biomass and foliage biomass of savanna ecosystems on a regional scale. Nevertheless the models need to be validated in more areas. Particularly further test sites with grass biomass values of 2 to 4 t/ha should be included to get a normal distribution of the values solving the problem discussed in figure 3. Involving more test sites would furthermore cover a greater variance of bioms and therefore secure the regional appliance. The different regression equations also have to be cross-checked by field measurements as presented and discussed before. Extending the current research could result in a single calibrated equation for each biomass type in savanna ecosystems of Southern Africa.

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