Zeitschrift: Botanica Helvetica

Herausgeber: Schweizerische Botanische Gesellschaft

Band: 111 (2001)

Heft: 1

Artikel: Assessing above-ground phytomass in an alpine region using a hand-held radiometer

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DOI: https://doi.org/10.5169/seals-73901

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Bot. Helv. 111 (2001): 73–85
0253-1453/01/010073-13 $ 1.50+0.20/0
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Botanica Helvetica

Assessing above-ground phytomass in an alpine region using a hand-held radiometer

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Manuscript accepted April 3, 2001

Abstract

Holzgang O. 2001. Assessing above-ground phytomass in an alpine region using a hand-held radiometer. Bot. Helv. 111: 73–85.

In the Swiss National Park, the damaging of sensitive vegetation was feared due to high densities of ungulates. In this context, data on the productivity of its grasslands and a non destructive method, alternative to clipping, for assessing above-ground phytomass were needed. In this study a hand-held radiometer which measured reflected radiance at 808 nm and 677 nm was used to assess the above-ground phytomass of subalpine and alpine grasslands (21 plots) and dwarf shrub associations (5 plots). The simple ratio (*SR*) was calculated by dividing the near-infrared reflected radiance (808 nm) by the one in red (677 nm). Diurnal series were carried out to examine the influence of time of day on *SR* and 26 plots were harvested to calibrate *SR* against clipped green and total phytomass. *SR* varied with solar time and was lowest at noon: It is therefore advisable to measure between 9:30 and 14:30 solar time. The plots of different grassland and dwarf shrub associations were pooled and categorised as 'grazed' (6 plots), 'ungrazed' (15 plots) or 'dwarf shrubs' (5 plots) for calibration of *SR* against phytomass and the dry weight of green and total above-ground phytomass was calculated separately for each category. The 95% confidence interval of prediction of the dry weight of green and total above-ground phytomass from the simple ratio (20 measurements) was ±28% and ±45%, respectively. Predictions of dry weight are reliable for ungrazed and dwarf shrub plots, because in contrast to grazed plots they were distributed over a wide range of phytomass. This fast, non-destructive method allows high numbers of replicates as well as monitoring of changes in above-ground phytomass of moderately grazed or ungrazed subalpine and alpine grasslands during successive years if at least 20 measurements are taken.

Key words: Dry matter yield, dry weight, grassland, simple ratio, vegetation indices.

Introduction

In the Swiss National Park, the discussion arose whether too many ungulates are grazing in its territory and thus are dominating the Parks area or even damaging sensitive vegetation

(Broggi 1995, Krüsi et al. 1995). Therefore, information on the grasslands' productivity was needed as a basis for wildlife management decisions. Because human influence should be minimized in the ecosystem of the Swiss National Park and because measurements had to be done in an alpine environment, an alternative method as radiometric measurements was needed to the tedious clipping of above-ground phytomass. Radiometric measurements can be done in short time and allow to remeasure the same plot at a later date to estimate changes in phytomass with time.

To date, radiometric methods have been more commonly applied to agricultural than to natural ecosystems for estimating leaf area index, standing crop, production and for indicating plant stress (e.g., Holben et al. 1980; Millard et al. 1980; Asrar et al. 1984; Lord et al. 1985; Kuusk 1991; Nilsson 1991; Daughtry et al. 1992; Mogensen et al. 1996; Casanova et al. 1998). Nevertheless, the vast literature allows to give general recommendations for the use of radiometric measurements in an alpine environment. Usually, the following two bands are chosen because of their strong difference of reflectance between green vegetation and the natural background: (1) 620–700 nm (red), where strong absorption by plant pigments occurs, and (2) 740–1100 nm (near infra-red), where minimal absorption occurs. Here, the leaf scattering results in high levels of spectral reflectance, especially for dense canopies (Knipling 1970; Tucker 1977; Tucker 1979; Mayhew et al. 1984; Tucker and Sellers 1986; Scurlock and Prince 1993). To have reliable values, at least 10–30% of the phytomass should be green vegetation (Pearson et al. 1976; Mayhew et al. 1984). To estimate the photosynthetically active phytomass the ratio of near infra-red to red (simple ratio, *SR*) or other combinations of the two bands are used. These ratios are usually based on estimates of reflectance (reflected radiance relative to incoming solar irradiance), but they may also be derived from absolute values of red and near infra-red reflected radiance, such as the values provided by satellites or aircraft sensors (Tucker 1979; Scurlock and Prince 1993).

This study focused on the usefulness and accuracy of a hand-held radiometer to determine the above-ground phytomass of different subalpine and alpine grasslands because not much was known about the application of radiometric measurements in an alpine environment. Additionally, the influence of time of day on the radiometric measurements of vegetation plots was investigated to give advice on when to take these measurements.

Methods

Site description

The study was conducted in the region of the Ofenpass in the Swiss National Park, which is located amongst the inner valleys of the Alps. The investigated grasslands and dwarf shrubs (Table 1 and Table 2) are situated mostly on calcareous soils or on a mixture of calcareous and siliceous soils (1750 m–2380 m a.s.l.). Two sites represent nutrient-rich subalpine grasslands which are heavily grazed by red deer (*Cervus elaphus* L.). The other sites are moderately grazed and belong to subalpine grasslands (3 sites), alpine grasslands (5 sites) or dwarf shrub associations (2 sites).

Radiometric measurements

The instrument used was a Tektronix J17 Photometer with a J1812 Irradiance sensor, which gives readings in W m^{-2} (Tektronix Inc., Oregon); the measuring accuracy was ± 8% of readings. The sensor was mounted on a hand-held boom, 90 cm in length. During measuring, the sensor was held perpendicular to the measured surface.

Measurements were carried out at 807.5 ± 3.5 nm (near-infrared, *NIR*) and 676.8 ± 10 nm (red, *R*). The filters (Balzers AG, Liechtenstein) were mounted on a rotatable disc and could be switched easily,

Table 1. Time course of SR: Site, date of measuring and plant association (nomenclature follows Zoller 1995) of the plots which were used for the diurnal series. Each plot was measured three times with the radiometer at hourly intervals. For subsequent calculations the mean of the three measurements was used.

Plot	Site	Date	Plant association
1	Stabelchod	21.7.95	Medicagini-Mesobrometum raeticum
2	II Fuorn	24.7.95	Trisetetum flavescentis
3	II Fuorn	24.7.95	Trisetetum flavescentis
4	II Fuorn	24.8.95	Trisetetum flavescentis
5	Labor	28.9.95	Seslerio-Caricetum sempervirentis
6	Labor	28.9.95	Seslerio-Caricetum sempervirentis
7	II Fuorn	24.7.95	Trisetetum flavescentis
8	II Fuorn	24.8.95	Trisetetum flavescentis
9	Labor	28.9.95	Seslerio-Caricetum sempervirentis
10	Labor	28.9.95	Seslerio-Caricetum sempervirentis

Table 2. Calibration of radiometric measurements against phytomass: Plant association (nomenclature follows Zoller 1995) and date of measuring of the plots which were measured first without a mask (5 radiometric measurements) and then with a mask (5 radiometric measurements) and afterwards clipped at ground-level for calibration of simple ratio against phytomass. The mean of the five measurements was used for subsequent calculations.

Plant association	Site	Date of measuring	
		Not grazed	Grazed
Nutrient-rich subalpine grasslands			
Trisetetum flavescentis	1	17.8.95 (3 plots), 4.7.96	17.8.95, 4.7.96
Crepido-Festucetum nigrescentis	2	15.8.95	15.8.95, 3.7.96, 15.7.96
Nutrient-poot subalpine or alpine grasslands			
Medicagini-Mesobrometum raeticum	3		4. 7. 96
Nardetum alpigenum typicum	4	18.7.96	
Seslerio-Caricetum sempervirentis	5–9	15.8.95, 16.8.95 (2 plots), 16.7.96, 20.7.96, 21.7.96, (2 plots)	
Trifolio-Festucetum violaceae	10	23.7.96 (2 plots)	
Dwarf shrub associations			
Junipero-Arctostaphyletum	11	21.8.96 (2 plots)	
Rhododendretum ferruginei	11	21.8.96 (2 plots)	
Rhododendretum hirsuti	12	18.7.96	

with a delay of about two seconds. The readings were stored in a pocket calculator and later transferred to a computer.

To calibrate the radiometric measurements against phytomass it is important to measure a clearly defined section of the sampled plot, because alpine and grazed grasslands are quite heterogeneous. Since from the used distance of 68 cm the sensor would cover nearly one square meter on the ground, a circular mask with a radius of 55.5 cm and a hole of 36 cm square in the middle was used to measure a 0.1296 m^2 plot of vegetation. The wooden mask was painted matt black with a commercially available wrought-iron coating. To standardise the measurements, I always measured with the sun to my right side and without casting shadow on the plot.

To investigate whether the black mask affected the *SR*, some plots were measured both with and without a mask. For measurements that were taken without a mask, the distance from surface to sensor was 101 cm and the angle of view was narrowed down with a tube to 20° which resulted in a measured area of 0.0995 m^2. For measurements without a mask, I positioned myself opposite to the sun.

It is important to notice that reflected radiance, as measured by satellite or aircraft sensors, and not reflectance was measured. Reflectance means the reflected radiance relative to a reference panel and is used in most studies. But with the use of a reference panel additional errors are introduced by the reflectance properties of the panel (Kimes et al. 1980).

For further calculations the simple ratio (*SR*) was used:

$$SR = \frac{NIR}{R} \qquad \text{eqn 1}$$

The measurements were carried out under conditions ranging from cloudless, partially covered to overcast sky. The only restriction that was imposed was that the irradiance should not change between the successive measurements of *NIR* and *R*.

Time course of SR

To examine the influence of time of day on the *SR*, diurnal series were carried out in July, August and September 1995 in three different grasslands in the Swiss National Park (Table 1). A total of 10 diurnal series were measured, three of them with a mask and two of them without a mask on both nutrient-rich (site Il Fuorn: Trisetetum flavescentis; nomenclature of plant associations follows Zoller 1995) and nutrient-poor grasslands (site Stabelchod: Medicagini-Mesobrometum raeticum; site Labor: Seslerio-Caricetum sempervirentis). Three radiometric measurements were taken at approximately hourly intervals from 8:00 to 17:00 CET. The mean of the three measurements was used for subsequent calculations.

For further calculations the local apparent solar time (*ST*) was used. It is calculated as follows: for each degree of longitude the site is east (west) of the standard meridian, 4 minutes are added (subtracted) from the local standard time (here: CET) and then the equation of time correction is algebraically added (Oke 1990).

For each diurnal series of the 10 plots investigated, the following model of time of day dependence was calculated:

$$SR = a + b\,(ST\ in\ minutes) + c\,(ST\ in\ minutes)^2 \qquad \text{eqn 2}$$

Calibration of SR against phytomass

Five radiometric measurements were taken first without and than with a mask on 26 plots (Table 2). The mean of the five radiometric measurements was used for subsequent calculations. To determine the green and the total above-ground phytomass, the vegetation of the 26 plots (0.125 m^2) was clipped at ground-level. The samples were separated into dead and green plant material, and dry weight (80 °C) of the components was determined.

Every measured plot was categorised as 'ungrazed', 'grazed' or 'dwarf shrub'. 'Ungrazed' stands for either ungrazed or slightly grazed grassland vegetation where only the tips of grasses or forbs have been taken. 'Grazed' means heavily grazed grassland vegetation in which grazing pressure has caused a shift from taller grasslands to a short turf. The distinction between ungrazed and grazed sites was not always clear, especially when the vegetation of the grazed plots was ungrazed for a period and grew taller than usual. But this was only the case for about 5% of the plots.

A general linear regression was calculated, in which the log of *SR* and the category were explanatory variables and the log of dry weight was the target variable:

$$\log(dry\ weight) = constant + \log(SR) + category \qquad \text{eqn 3}$$

The resulting intercept α and coefficients β, γ and δ were used to calculate the phytomass as follows:

$$dry\ weight = 10^{\alpha + \gamma}\, SR^{\beta} \quad \text{(grazed)} \qquad \text{eqn 4}$$
$$dry\ weight = 10^{\alpha + \delta}\, SR^{\beta} \quad \text{(ungrazed)} \qquad \text{eqn 5}$$
$$dry\ weight = 10^{\alpha - \gamma - \delta}\, SR^{\beta} \quad \text{(dwarf shrub)} \qquad \text{eqn 6}$$

Results

Time course of SR

All diurnal series that were measured with a mask showed a significant ($P < 0.05$ of the regression of equation 2) time of day dependence of the *SR* (Table 3). All series showed a similar pattern with the lowest values at about 1 h after solar noon (Fig. 1). Of the diurnal series that were measured without a mask, two plots showed a significant dependence of *SR* on time of day (Table 3), though the trends are similar to those measured with a mask (Fig. 2). There is no difference between nutrient-rich and nutrient-poor grasslands.

If only values which were measured between 9:30 and 14:30 *ST* were taken, only one of 10 diurnal series showed a significant time of day dependence of *SR*.

Calibration of SR against phytomass

Dry weight of green plant material

All regressions showed a good coefficient of determination ($R^2 > 0.896$, Table 4). For regressions both with and without a mask R^2 increased and the mean square of the error declined if only *SR* values between 9:30 and 14:30 were included in the regressions. The best model

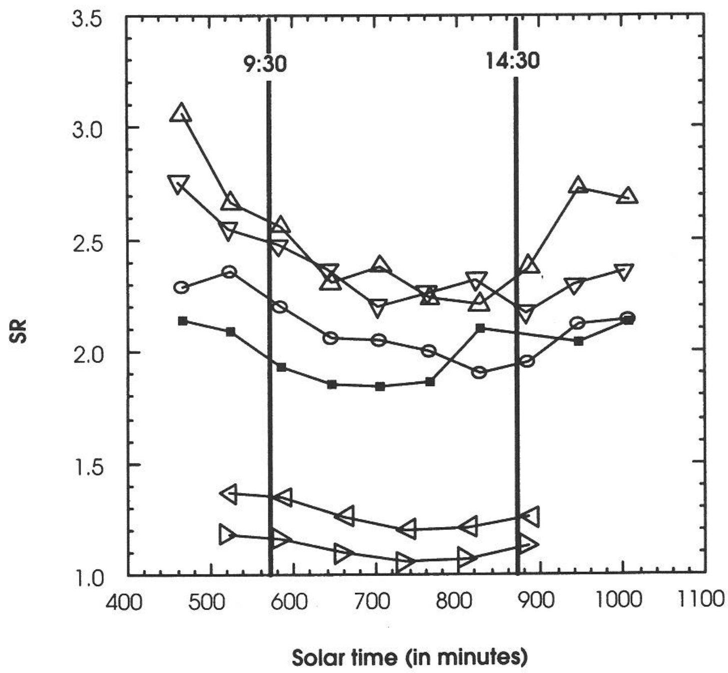

Fig. 1. The daily course of the simple ratio (*SR*) for the six plots which were measured with a mask. Site Stabelchod: ■, plot 1. Site II Fuorn: ○, plot 2; △, plot 3; ▽, plot 4. Site Labor: ◁, plot 5; ▷, plot 6.

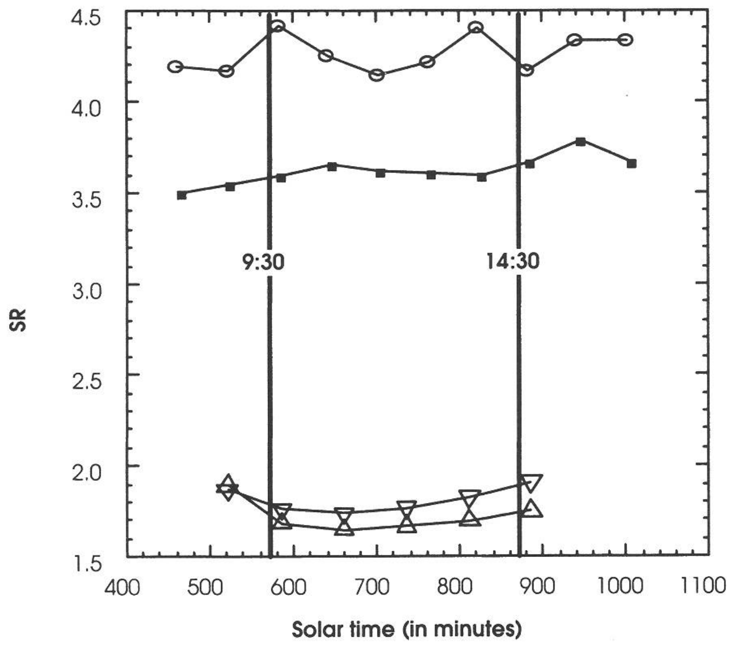

Fig. 2. The daily course of the simple ratio (*SR*) for the four plots which were measured without a mask. Site Il Fuorn: ■, plot 7; ○, plot 8. Site Labor: △, plot 9; ▽, plot 10.

Table 3. Significance of the regressions of equation 2 for diurnal series which were measured with a mask (+) and without a mask (–). For the models 'All *SR* values' all hourly measurements were included whereas for the models '9:30 – 14:30' only *SR* values which were measured between 9:30 and 14:30 solar time were included. Plot 1 is from the first nutrient-poor site, plots 5, 6, 9 and 10 are from the second site. Plots 2–4, 7 and 8 are from the same nutrient-rich site. ***, $P \leq 0.001$; **, $P \leq 0.01$; *, $P \leq 0.05$; ns, $P > 0.05$; *N*, number of hourly measurements.

Plot	Mask	Model			
		All *SR* values		9:30 – 14:30	
		P-Value	*N*	*P*-Value	*N*
1	+	*	9	ns	5
2	+	**	10	ns	5
3	+	***	10	ns	5
4	+	***	10	ns	5
5	+	*	6	ns	4
6	+	*	6	ns	4
7	–	*	10	ns	5
8	–	ns	10	*	5
9	–	ns	6	ns	4
10	–	*	6	ns	4

for determining green plant material was measuring without a mask between 9:30 and 14:30 ST. The estimates of the regressions against the log of the clipped dry weight of the green phytomass are shown in Fig. 3. Dry weight of ungrazed and dwarf shrub plots were distributed over a wide range of phytomass, whereas four of the five grazed plots had a similar

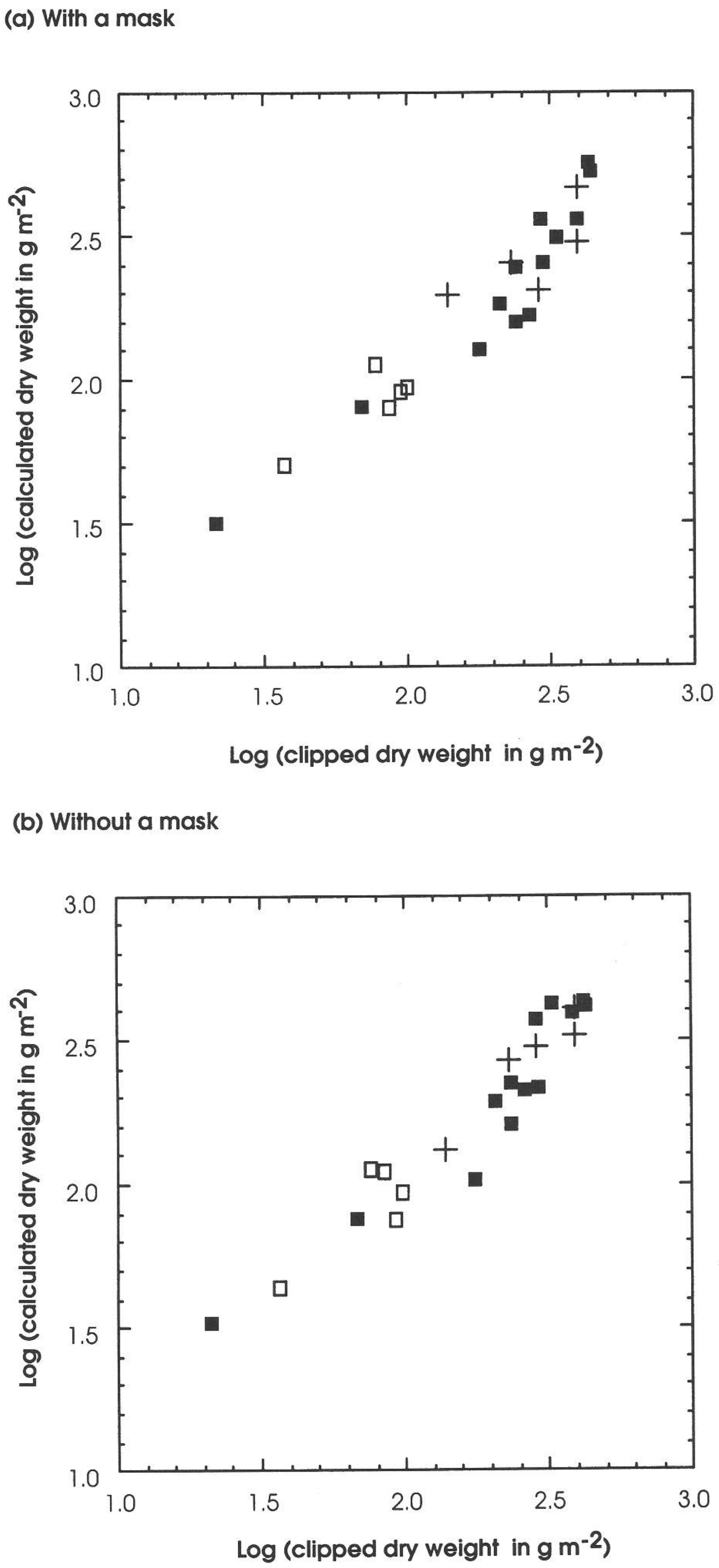

Fig. 3. Comparison of calculated and clipped dry weight of green phytomass for ungrazed (■), grazed (□) and dwarf shrub plots (+). The dry weight was calculated by using the regression parameters from Table 4 (row 1 for Fig. 3a; row 3 for Fig. 3b) in eqn 4 to 6.

Table 4. Regression parameters and 95% confidence intervals of prediction (for 1, 10 and 20 measurements) of different models for calculating the dry weight of green and total phytomass applying eqn 3. The models having SEpred values and confidence intervals are shown in Fig. 3 and Fig. 4.
Mask, measurements were taken with a mask (+) or without a mask (–); R^2, α, β, γ, δ, regression parameters resulting from application of eqn 3; Mean square, mean square of error; *N*, number of plots included in regression; SEpred, mean standard error of prediction; †, only *SR* values which were measured between 9:30 and 14:30 *ST* were included in regression.

Mask	R^2	α	β	γ	δ	Mean square	*N*	SEpred	Confidence interval (in %)			
									1	10	20	
Green plant material												
+	0.901	1.85	1.81	–0.343	0.085	0.0141	23	0.048	85	34	30	†
+	0.896	1.84	1.81	–0.372	0.099	0.0148	26					
–	0.917	1.63	1.36	–0.384	0.105	0.0119	23	0.044	76	31	28	†
–	0.904	1.62	1.35	–0.412	0.115	0.0136	26					
Total plant material												
+	0.786	2.16	1.91	–0.288	–0.022	0.0353	23					†
+	0.794	2.15	1.93	–0.296	–0.020	0.0314	26	0.067	147	52	45	
–	0.744	1.96	1.36	–0.327	–0.001	0.0423	23					†
–	0.749	1.94	1.37	–0.336	–0.003	0.0383	26	0.074	171	59	51	

clipped dry weight. Therefore, predictions of dry weight for grazed plots should be done with caution.

The 95% confidence intervals for the prediction of the actual dry weight from a single *SR* value were ±76% and ±85% for measurements without and with a mask, respectively. The confidence interval of prediction depends on the number of replicates and it reduces for 20 measurements to ±28% and ±30% for measurements without and with a mask, respectively. Hence the prediction of the dry weight was almost independent of the use of a mask.

Dry weight of total plant material

All regressions showed a R^2 greater than 0.744 (Table 3). In contrast to the dry weight of green plant material, R^2 declined and the mean square of the error increased slightly if only *SR* values between 9:30 and 14:30 were included in the regression, although both green and total plant material were from the same plot. Fig. 4 shows the estimates of the regressions against the log of the clipped dry weight of the total phytomass. The values of the three categories – ungrazed, grazed and dwarf shrub – are more scattered than in Fig. 3. All grazed plots are grouped together which means that for this group no predictions should be made for total plant material.

The 95% confidence intervals for the prediction of the actual dry weight from a single *SR* value were ±171% and ±147% for measurements without and with a mask, respectively. The confidence interval of prediction reduces for 20 measurements to ±51% and ±45% for measurements without and with a mask, respectively. Also, in contrast to the phytomass of green plant material, the prediction of the dry weight was slightly more accurate if *SR* values were measured with a mask.

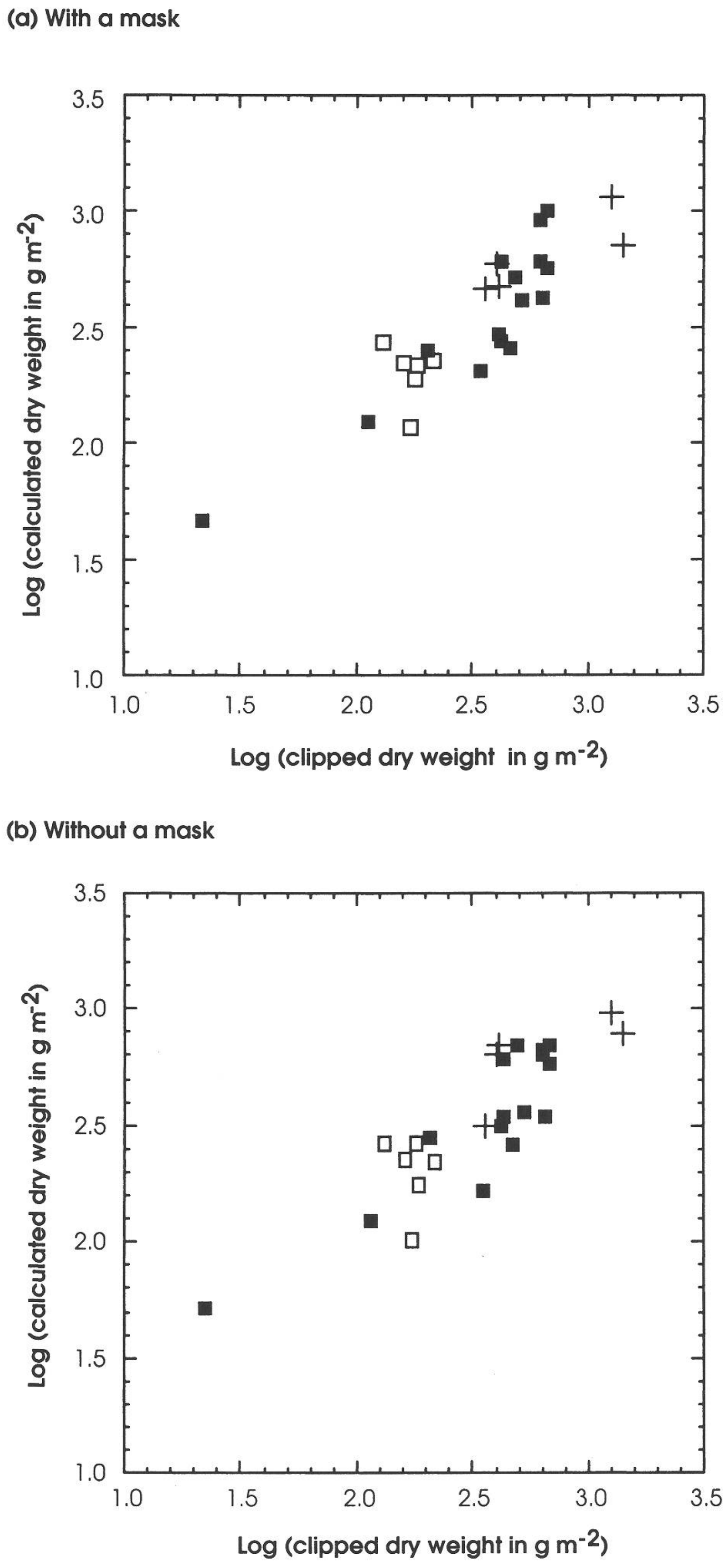

Fig. 4. Comparison of calculated and clipped dry weight of total phytomass for ungrazed (■), grazed (□) and dwarf shrub plots (+).The dry weight was calculated by using the regression parameters from Table 4 (row 6 for Fig. 4a; row 8 for Fig. 4b) in eqn 4 to 6.

Discussion

Precision of radiometric measurements

The different diurnal series showed that the simple ratio (*SR*) depended on time of day and generally was lowest at noon. Kimes et al. (1984) and Duggin (1977) also reported an increasing spectral reflectance with increasing solar zenith angle, i.e. with increasing deviation of noon. The latter found changes in reflectance of wheat of 25–50% with a 30° change in solar zenith angle. Middleton (1991), too, reports increasing *SR* with increasing solar zenith angle for prairie sites with a leaf area index of 0.5 to 2, whereas taller or denser vegetation (leaf area index > 2) exhibited either a maximum value at solar noon which decreased as solar zenith angle increased, or a moderate to high *SR* which remained approximately constant. Kimes et al. (1980) actually measured a decrease in reflectance for increasing solar zenith angle. Middleton (1991) concludes that a general "correction" to remove sun angle effects on spectral ratios is inappropriate because of the great variation of *SR* responses as a function of solar zenith angle. This corresponds with my results: diurnal series which were measured with a mask showed a clear pattern, whereas the ones which were measured without a mask did not show such uniform behaviour. Instead of looking for a correction I recommend to measure around solar noon, as in this study only 1 of 10 diurnal series showed a significant dependence of *SR* on time of day when only measurements of *SR* between 9:30 and 14:30 were used, compared to 8 out of 10 series of *SR*-measurements between 8:00 and 17:00.

This dependence of *SR* on time of day is likely caused by vegetation. Kimes et al. (1980) found that in August the near-infrared (780–1400 nm) and red (620–700 nm) reflectances of a meadow were lower in the afternoon than in the morning at the same solar zenith angle, whereas in spring no difference could be detected. According to Tucker and Sellers (1986), the correlation of radiometric data with leaf area index depends on leaf orientation and solar elevation for canopies with non-horizontal leaf angle distribution functions. Kimes (1984) points out that the orientation distribution can change on a diurnal basis because of heliotropic leaf movements and other responses to environmental conditions. These small perturbations in leaf geometry may drastically alter the reflectance distribution.

Other factors such as clouding or dust can influence the spectrum of the incoming solar beams and thus change the recorded ratio of near-infrared to red. Between the hourly measurements the weather often fluctuated considerably from sunny, slightly overcast to dull conditions. The effect of clouds is found to be about 5% (Holmes and Smith 1977), resulting in a significant increase of the *SR* reading (Mayhew et al. 1984). A solution is to take measurements of the spectral reflectance of natural surfaces under conditions of uniform irradiation such as bright sunshine or a uniform overcast day (Milton 1981). However, random weather variations of at least 5–10% can occur, even on apparently clear days (Duggin and Philipson 1982), and high altitude cirrus clouds passing in front of the sun are difficult to detect with the human eye (Milton 1982). Additionally, uniform irradiation conditions rarely persist for significant periods during a day in alpine regions.

It seems as if an error of about ±10–15% the measurements of reflectance cannot be avoided, even if the measurements are taken under apparently uniform conditions.

Phytomass assessment with radiometric measurements

Many studies of phytomass using radiometric techniques are restricted to only one vegetation type (Pearson et al. 1976; Mayhew et al. 1984; Kuusk 1991; Middleton 1991; Das et al. 1993). In the present study, however, plots of six different grassland and three different dwarf shrub associations were included. Since vegetation structure as e.g. leaf angle or leaf transmittance rather than the plant association is of paramount importance for the calibration of simple ratio (Kimes 1984; Kuusk 1991; Scurlock 1992; Scurlock and Prince 1993), the studied vegetation plots were categorised as grazed, ungrazed of dwarf shrub. This resulted in a reliable $R^2 > 0.90$ and $R^2 > 0.74$ for the calibration of green and total phytomass, respectively.

The 95% confidence interval for the prediction of the actual dry weight amounted for 20 measurements to ±28% and ±45% for the green and total phytomass, respectively. In contrast to ungrazed and dwarf shrub plots the dry weight of grazed plots was clustered and therefore predictions of dry weight should be done with caution. A comparison of the accuracy of prediction with regressions described in literature is difficult, because this information is lacking. R^2 can be compared, though, and for total phytomass values of 0.76 for winter wheat (Tucker et al. 1981) or 0.96 for sample plots of blue grama (*Bouteloua gracilis*) (Pearson et al. 1976) are found. For green phytomass, values between 0.53 and 0.74 were measured in stocked ryegrass pastures (King et al. 1986) or 0.92 in a damp meadow (Mayhew et al. 1984). Usually, the prediction for green phytomass is more accurate than for total phytomass, because the photosynthetically active tissue interacts with the red portion of the light spectrum, which is measured and used as denominator for the calculation of the *SR* (Knipling 1970; Tucker 1977; Mayhew et al. 1984; Scurlock and Prince 1993).

The use of a black mask did not increase the accuracy of determining the dry weight of green phytomass in heterogeneous vegetation, although the plots that were clipped for calibration were clearly defined. For determining the dry weight of total phytomass the use of a black mask increased slightly the accuracy which rather seems due to chance than to the mask. In conclusion, the method is useful for assessing phytomass of moderately grazed or ungrazed subalpine and alpine grasslands as well as dwarf shrub associations if at least 20 measurements are taken per vegetation type. It is recommended to measure between 9:30 and 14:30 solar time. To validate the measurements selected plots should be clipped.

I am grateful for useful advice in planning the work to Andreas Gigon and Otto Hegg and to Gérald Achermann, Markus Hofbauer and others who assisted in the field work, and to the staff of the Geobotanical Institute ETH, and the Systematical and Geobotanical Institute of the University of Bern for their help. I would also like to thank Peter J. Edwards, Flurin Filli, Lukas Kohli, Johannes Kollmann, Moni Pfunder, Caroline Roggo and an anonymous reviewer for helpful comments on the manuscript. This project was funded by the Swiss National Park.

Zusammenfassung

Die hohen Huftierdichten im Schweizerischen Nationalpark führten zu Diskussionen über deren Einfluß auf die Vegetation. In diesem Zusammenhang wollte man mehr über die Pflanzenproduktion der natürlichen subalpinen und alpinen Grasland- und Zwergstrauchgesellschaften wissen und suchte eine nicht-destruktive Alternative zur üblicherweise angewendeten Erntemethode. In der vorliegenden Studie wurde deshalb zur Bestimmung der Phytomasse mit einem Radiometer die von der Vegetation reflektierte Strahlung in den Wellenlängen 808 nm (nahes Infrarot) und 677 nm (rot) gemessen. Für die Berechnungen wurde das Verhältnis 808 nm zu 677 nm verwendet, das sogenannte „simple ratio" (SR). Um den Einfluß des Sonnenstandes auf die Messungen zu untersuchen, wurden Meßreihen mit stündlichen Messungen durchgeführt. Die SR-Werte variierten mit dem Sonnenstand und waren um die Mittagszeit am tiefsten. Bei 26 Flächen wurde die Vegetation auf Bodenhöhe abgeschnitten und in grüne und tote Pflanzenmasse sortiert, um die SR-Werte anhand der vorhandenen

Phytomasse zu eichen und die Meßgenauigkeit zu bestimmen. Bei 20 Radiometermessungen beträgt das 95-prozentige Vertrauensintervall für die Vorhersage der grünen Pflanzenmasse ±28% und für jene der totalen Pflanzenmasse ±45%. Die schnelle, nicht-destruktive Radiometermethode erlaubt viele Wiederholungen und ein Monitoring der oberirdischen Phytomasse in wenig oder nicht beweideten Grasland- und Zwergstrauchgesellschaften.

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