BOREAL ENVIRONMENT RESEARCH 13: 417–432
ISSN 1239-6095 (print) ISSN 1797-2469 (online) Helsinki 31 October 2008

Normalized difference vegetation index (NDVI) in the management of mountain meadows

Zuzana Mašková[1)], František Zemek[2)*] and Jan Květ[2)3)]

[1)] *Administration of the Šumava National Park and Protected Landscape Area, CZ-342 01 Sušice, Czech Republic*
[2)] *Institute of Systems Biology and Ecology AS CR, v.v.i., Na Sádkách 7, CZ-370 05 České Budějovice, Czech Republic (corresponding author's e-mail: f.zemek@usbe.cas.cz)*
[3)] *Faculty of Biological Sciences, University of South Bohemia, Branišovská 31, CZ-370 05 České Budějovice, Czech Republic*

Received 25 Jan. 2007, accepted 20 Oct. 2007 (Editor in charge of this article: Eevastiina Tuittila)

Mašková, Z., Zemek, F. & Květ, J. 2008: Normalized difference vegetation index (NDVI) in the management of mountain meadows. *Boreal Env. Res.* 13: 417–432.

The aim of the study was to test the possibility of using the Normalized Difference Vegetation Index (NDVI) for distinguishing between differently managed mountain grassland sites surrounded by boreal forests. The NDVI was assessed under field conditions in three differently managed meadows (mown, mulched, unmanaged), at an altitude of 1150 to 1170 m in the Bohemian Forest Mts. The mowing and mulching were applied to the respective plots in mid-July and three successive NDVI/aboveground biomass assessments were made before and two after the application of the treatments. The presence of litter, expressed by the green ratio index (GR), strongly affected the reflectance of the grassland canopy. The linear relationships between green biomass and NDVI were statistically significant for all treatments only during the period before the application of the treatments. It was only in the unmanaged plot that a statistically significant linear relationship between NDVI and GR was recorded.

Introduction

Changes of agricultural policy in central Europe at the end of the 20th century resulted in abandonment of extensive areas of secondary mountain meadows and pastures which replaced a part of boreal forests in the past. The existence and quality of secondary grassland depend, however, fully on human management. New alternative practices of non-profit grassland management are necessary. There is also a need to find methods for evaluating the management impacts.

Aerial photography, and since 1960s remote sensing (RS), became an important and indispensable source of data about the Earth surface and processes. Increasing both spatial (from km to cm) and spectral resolution (from wide band range to narrow hyperspectral) of RS data make it possible to work on different scales and at different information levels. Digital imagery analyses are powerful tools for mining information from these data. Innumerable algorithms exist to extract specific information from certain data sources: from simple threshold to contextual classifications based on neural nets.

Many attempts were made to find "simple" approaches, including the use of vegetation indices (VIs). The VIs are spectral transformations of two or more bands. They are computed directly without any bias or assumptions regarding the land cover class, soil type, or climatic conditions. The number of VIs significantly increased especially after hyperspectral RS data became a standard part of vegetation monitoring, and offered an unlimited number of band combinations (e.g., Broge and Leblanc 2001, Zarco-Tejada *et al*. 2001, le Maire *et al*. 2004).

The VIs derived from field/airborne/satellite data display substantial empirical, and in many cases theoretical, evidence that they are related to several vegetation parameters. As a result, many VIs are tested for estimation of different vegetation properties such as biophysical parameters of vegetation (McDonald *et al*. 1998, Huete *et al*. 2002, Elwadie *et al*. 2005), quantification of vegetation biomass (Zheng *et al*. 2004, Lu 2006), determination of different phenological phases (Zhang *et al*. 2003), monitoring of stress effect (Eklundh 1996, McVicar and Jupp 1998), precision farming (Moran *et al*. 1997, Haboudane *et al*. 2004), and monitoring of such natural vegetation as that of prairies (Senay and Elliott 2000, Barbosa *et al*. 2006).

The normalized difference vegetation index (NDVI) is historically one of the first VIs. It is a normalized ratio of the NIR (near infrared) and red bands (Rouse *et al*. 1974):

$$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{Red})/(\mathrm{NIR} + \mathrm{Red})$$

The NDVI was used in numerous studies to estimate vegetation biomass, greenness, primary production, dominant species, leaf area index (LAI), fraction of absorbed photosynthetically active radiation (fAPAR) (e.g. Myneni and Williams 1994, Koide *et al*. 1998, Gopal *et al*. 1999, Senay and Elliott 2000, North 2002, Kawamura *et al*. 2005, Pettorelli *et al*. 2005, Telesca *et al*. 2006). The NDVI is also an important parameter in various kinds of local, regional, and global scale models, including general circulation and biogeochemical ones.

The NDVI images derived from the Advanced Very High Resolution Radiometer of the National Oceanic and Atmospheric Administration (NOAA-AVHRR) provide opportunities for time-series analyses of changes in land use and cover on global scale (Fuller 1998). Recently, also the Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI, referred to as the "continuity index" to the existing 20+ year NOAA-AVHRR, derives NDVI time series and aims to provide a longer-term data record for use in operational monitoring studies. Huete *et al*. (2002) give an overview of the operational applicability of the MODIS vegetation indices.

The main disadvantage of the NDVI is the inherent non-linearity of ratio-based indices and the influence of additive noise effects, such as atmospheric path radiances. The NDVI also exhibits symptotic (saturated) signals over high biomass conditions. It means that NDVI based on the red and near-infrared portions of the electromagnetic spectrum asymptotically approaches a saturation level beyond a certain biomass density or LAI. Mutanga and Skidmore (2004) suggested hyperspectral narrow band indices in order to overcome the saturation in biomass estimation. This is, however, hardly applicable on a cheap and operational local/regional scale that was in the focus of our research. The saturation effect occurs typically in multilayer vegetation such as forests or agricultural crops, with LAI > 4 (Baret and Guyot 1991, Gobron *et al*. 1997).

In this study, run for one vegetation season, we tested, in a field experiment (*in situ*), the reaction of the NDVI to the biomass of semi-cultural mountain meadows subjected to three types of management. The management included mowing, mulching, and fallow, i.e., no management. The respective management practices (further on "treatments") were applied each year starting from 1997, and we carried out the study in 2001. We related the NDVI both to the green biomass and the herbage green ratio (GR) index (Tucker 1980, Vescovo and Gianelle 2006). We also considered the importance of the species composition of the meadows for the NDVI.

We assumed that the problem of saturation could hardly occur in mountain meadows. An average LAI of grassland was estimated at 2.5 (Scurlock *et al*. 2001); moreover, the presence of litter and standing dead plant material (further on only "litter") affects the reflectance. The green biomass in mulched plots is affected (partly masked) by dry biomass left over from mulching in the previous year and, after mulching, also by that of the current year. In the unmanaged plot, green biomass has to grow through standing dead plant remnants from the previous year(s). The NDVI of the mown plot can be affected by soil backscattering both at the beginning of the vegetation season and after mowing.

The aim of this study was to test the use of NDVI for distinguishing between different treatments of mountain meadows, namely between their mowing, mulching and fallow management.

The following questions can be asked:

1. Do changes of NDVI values during the growing season really correspond to seasonal changes of live (green) plant biomass and/or the GR in mountain meadows?
2. Does the amount of plant litter lower the NDVI values in comparison with those for sites with much the same amount of live plant biomass, but less litter?
3. Is there a difference between NDVI values of mountain meadows subjected to the three different treatments?
4 Do the results obtained have practical implications? Is it possible to use the NDVI for identifying mulched, mown and unmanaged mountain meadows?

Material and methods

Study site

The study site was situated in the Šumava National Park and Biosphere Reserve, Czech Republic (49°05´N, 13°33´E). The experimental species-rich mountain meadow lay in an isolated grassland enclave within a forested area (Boreal forest with dominant Norway spruce, *Picea abies*) below the top of Huťská hora Mt. (1187 m above sea level), about 8 km to the North of the settlement Kvilda. For a detailed description and history of the whole study site and surrounding area, *see* Mašková *et al*. (2001a, 2001b).

The experimental site was 300 × 400 m large, on a SW-facing slope, inclination to l0°, the altitude of the site ranging between 1150 and 1170 m. Climatic conditions and the underlying paragneiss parent rock gave rise to acidic brown soils (Acid Dystric Cambisol; Kvítek *et al*. 2001).

The vegetation on the experimental site was, in phytocenological terms, an acidophilous meadow, *Cardaminopsio halleri–Agrostietum* association, *Polygono–Trisetion* alliance (Moravec 1965), dominated by *Deschampsia cespitosa, Festuca rubra, Agrostis capillaris* and *Hypericum maculatum*, with diagnostic species *Cardaminopsis halleri, Melandrium sylvestre, Phyteuma nigrum, P. spicatum,* and *Veronica chamaedrys* (Table 1). The data used for assessing the average cover percentages are based on phytocenological relevés recorded in 1997 to 2000 (Zelený *et al*. 2001).

Experimental design

In 1997, we established three permanent experimental plots — 50 × 100 m each — subjected to different treatments (Fig. 1).

We compared three alternative treatments:

1. Mowing and drying of the vegetation to produce hay. We subsequently removed the hay from the mown plot. The mowing treatment followed a régime corresponding to standard low-impact agricultural practice typical of highland regions of central Europe: mowing once in a year (in July, in our experiment on 19 July 2001), employing low impact mechanization.
2. Mulching of the second plot. This treatment involved cutting and crushing of the vegetation and leaving it to decompose on the spot. The mulching treatment is new to the highland regions: it consists of mulching the grassland vegetation once a year (in our experiment on 19 July 2001).
3. Leaving the third plot fallow, allowing for a spontaneous vegetation development from the start of the experiment, with no management. We included the fallow treatment because large areas of mountain meadows are nowadays abandoned and left to spontaneous succession.

Phytocenological assessment (Zelený *et al*. 2001; D. Šraitová unpubl. data) confirmed that after four years (1997–2000) of the same management the vegetation reached a certain level of

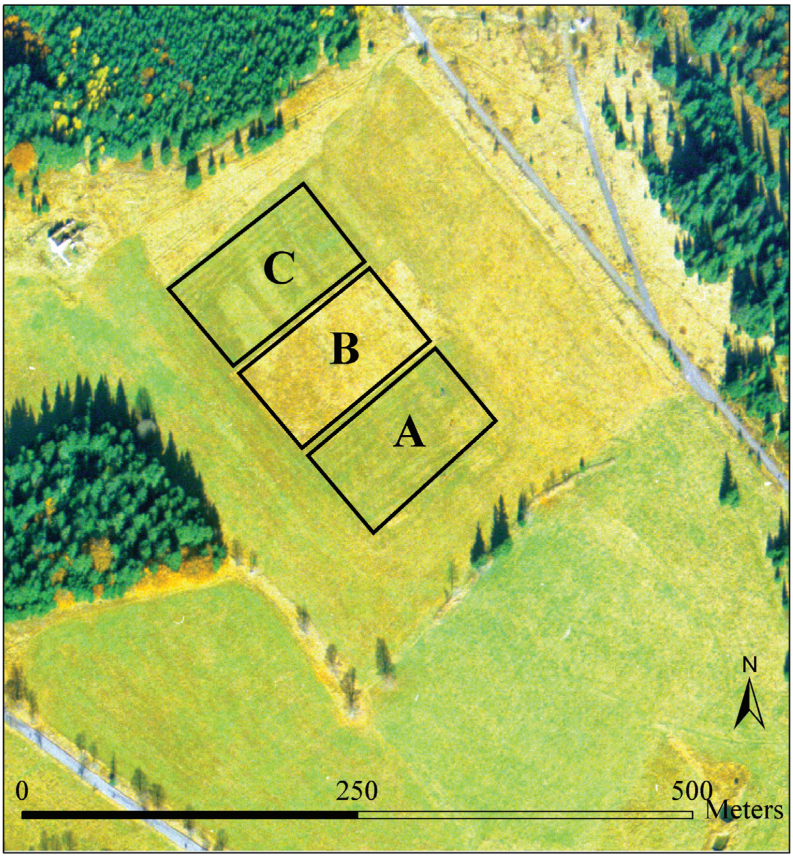

Fig. 1. Aerial view (2000) of the part of the Zhůří enclave showing the position of the experimental site and plots. A: mown stand, B: unmanaged (fallow) stand, C: mulched stand.

homogeneity in each of the treated plots.

We used a Dycam Agricultural Digital Camera (ADC, Dycam Inc., Chatworth, CA, USA) that is frequently used in data acquisition for NDVI calculation in research studies (e.g., White *et al*. 2000, Nagler *et al*. 2001, Nagler *et al*. 2004) and also in practical applications, e.g., mapping of plant stress (Hughes *et al*. 2000). The ADC was tailored for multi-band photography in the red (635–667 nm) and near infrared NIR (835–870 nm) wavebands, with spatial resolution of 496 × 365 pixels, the lens having a fixed f of 4.5. The field of view was equivalent to that of a lens with 60 mm focal length in 35 mm film format.

On 24 May, 20 June, 19 July, 16 August and 20 September 2001, vegetation season, we sampled the aboveground plant biomass and litter from the same 0.33 × 0.33 m quadrats in which we also measured the NDVI values, with four replicate samples for each treatment. After assessing the fresh weight, we assessed the dry weight of each sample following its drying to constant weight at 85 °C.

To estimate plant species composition, we established 15 permanent plots of 1 × 1 m each, five in each of the three differently treated plots.

Data acquisition

We conducted both the measurement of the vegetation indices and the sampling of plant biomass five times during the 2001 growing season: three times (24 May, 20 June, 19 July) before applying the experimental treatments, and twice (16 August and 20 September) after mulching and mowing the two respective plots. We took comparative phytocenological relevés before applying the experimental treatments in July 2001.

We mounted the ADC camera on a tripod on an arm to take vertical photographs of sample plots of the size exceeding 0.33 × 0.33 m from the height of 1.5 m, with four replicates per each plot where we harvested the biomass samples. Before this procedure, we took a calibration photograph. This we did by installing the red filter, placing a calibration diffuser across the lens and taking a photograph of a white plastic sheet. We applied the calibration values to all images made under the calibrated conditions. After taking the calibration photograph, we removed the diffuser and left only the red filter when taking photographs of the respective plots of the vegetation. We scanned all images under clear sky between 12.00 and 13.00 in order to minimize the pattern of shadows within the vegetation. The Sun's zenith angle (including slope of the plot) and azimuth at 12.30 were as follows: 18.1° and 194.6° on 24 May; 16.3° and 195.7° on 20 June; 19.4° and 194.5° on 19 July; 24.4° and 192.4° on 16 August; 39.5° and 189.9° on 20 September.

We cut off the aboveground plant parts about 1 cm above soil surface. From a known area, we raked out the lodged or fallen off and slowly decomposing dead plant material and litter. The litter biomass inevitably included also the practically inseparable biomass of bryophytes penetrating the gradually decomposing litter originating from aboveground plant parts.

We divided each permanent plot of 1 × 1 m into nine sub-plots, using a wire square grid of nine cells of 0.33 × 0.33 m each. We estimated the combined abundance and cover degree of each vascular plant species in each sub-plot, using the Braun-Blanquet seven-degree scale (Braun-Blanquet 1964). Plant nomenclature follows that of Kubát *et al*. (2002).

Table 1. List of species recorded in the experimental mountain meadow site and their approximated abundance in the sample plots.

Species	Cover (%)	Species	Cover (%)
Acer pseudoplatanus (juv.)	< 0.01	*Lilium bulbiferum*	< 0.01
Achillea millefolium	0.09	*Luzula campestris*	< 0.01
Agrostis capillaris	12.73	*Luzula luzuloides*	4.15
Alchemilla sp.	< 0.01	*Luzula multiflora*	0.21
Alopecurus pratensis	< 0.01	*Luzula pilosa*	< 0.01
Anemone nemorosa	< 0.01	*Phleum pratense*	< 0.01
Anthoxanthum odoratum	1.04	*Phyteuma nigrum*	< 0.01
Arnica montana	< 0.01	*Phyteuma spicatum*	< 0.01
Avenella flexuosa	< 0.01	*Pimpinella saxifraga*	< 0.01
Bistorta major	< 0.01	*Poa pratensis*	0.85
Campanula rotundifolia	0.38	*Potentilla erecta*	0.16
Cardaminopsis halleri	1.26	*Ranunculus acris*	0.03
Carex ovalis	< 0.01	*Ranunculus repens*	< 0.01
Carex pilulifera	< 0.01	*Rhinanthus minor*	< 0.01
Carlina acaulis	< 0.01	*Silene dioica*	3.00
Cerastium arvense	< 0.01	*Soldanella montana*	< 0.01
Cerastium holosteoides	< 0.01	*Rumex acetosa*	0.26
Cirsium heterophyllum	0.03	*Rumex acetosella*	0.88
Cirsium palustre	< 0.01	*Sorbus aucuparia* (juv.)	< 0.01
Deschampsia cespitosa	28.13	*Stellaria graminea*	0.06
Festuca pratensis	< 0.01	*Taraxacum* sp.	0.08
Festuca rubra	35.11	*Trifolium medium*	< 0.01
Galeopsis tetrahit	< 0.01	*Trifolium repens*	0.70
Galium album	< 0.01	*Veronica chamaedrys*	0.77
Gnaphalium sylvaticum	< 0.01	*Veronica serpyllifolia*	< 0.01
Hieracium aurantiacum	0.06	*Vicia cracca*	< 0.01
Holcus lanatus	< 0.01	*Vicia villosa*	< 0.01
Holcus mollis	< 0.01	*Viola tricolor*	0.01
Hypericum maculatum	20.00		

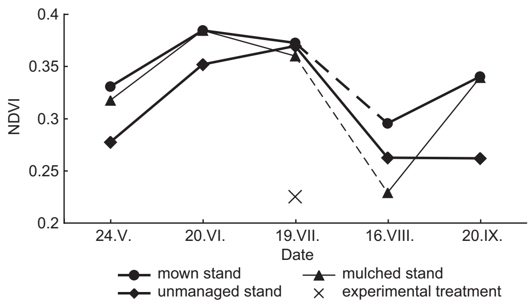

Fig. 2. Seasonal changes of the vegetation index (NDVI) in mountain grassland stands subjected to three treatments: mulching, mowing once a year, and no management.

Data evaluation

We used a vector mask delineating the boundary of a rectangle of 0.33 × 0.33 m (with the vegetation afterwards harvested for biomass assessment) within each photograph. We split regularly such a quadrat into nine (3 × 3) fields of 11 × 11 cm each. We used BRIV32 (Band Ration Image Viewer) software delivered by Dycam Inc. (Heinold 2000) to calculate the NDVI for each of the nine fields. We also calculated the means and standard deviations of nine NDVI values. These two numbers characterized the NDVI of each plot and we used them in subsequent statistical procedures.

We used the values of dry plant biomass in analyses of the relationship between the plant biomass (both in g m^{-2}) and the NDVI, and in the calculation of the GR index:

GR = green biomass/(green biomass
+ standing dead and litter biomass)

To estimate plant species composition, we averaged the cover values for individual species in each of the nine sub-plots within each experimental 1 × 1 m plot. We evaluated statistically the resulting five phytocenological relevés representing each treatment as five replicates for each treatment.

We applied the correlation and regression analyses (Statistica ver. 7) to the data obtained in order to express the relationship between plant aboveground fresh biomass and NDVI, and that between GR and NDVI, for each treatment. This we did for two data sets of corresponding biomass-NDVI, GR-NDVI pairs. The first set included data from the measurements carried out before applying the treatments (mowing, mulching). This accounts for 12 green biomass-NDVI pairs and 12 GR-NDVI pairs. The other set included data acquired after the treatments (8 green biomass-NDVI pairs and 8 GR-NDVI pairs).

For each of the data sets we calculated both the correlation coefficients and linear regressions (includeing 95% confidence interval) between the biomass and NDVI and GR, respectively.

We tested the differences between different treatments on each of the five sampling dates in 2001 for the following parameters: NDVI, GR, dry green biomass, dry litter biomass.

First, we used the Kruskal-Wallis ANOVA by rank test to test the hypothesis on equality of respective parameters for each date. Then, we applied the Mann-Whitney *U*-test to test for differences between the respective pairs of treatments for those dates on which the Kruskal-Wallis ANOVA was significant ($p < 0.05$).

Results

The mown plot displays the highest NDVI values throughout the whole growing season (Fig. 2). The values for the mulched plot recorded before the treatment followed a similar trend, but there was a significant clump in the first measurements after applying the treatment (Fig. 2). The unmanaged fallow plot showed the lowest values of NDVI both before the maximum biomass was attained and at the end of the growing season (Fig. 2).

The values of NDVI were quite homogeneous within treatments during the whole sampling season. The coefficients of variation of the NDVIs calculated from nine values of each sampled quadrat ranged between 2% and 6%, with an extreme of 8% for the mulched plot after the treatment (16 August). This coefficient calculated for all 36 plots (11 × 11 cm) within each treatment on the respective days ranged between 4% and 8%, with an extreme of 13% for the mulched plot after the treatment (16 August).

We obtained statistically significant differences between the NDVI values for the mulched, mown and unmanaged (fallow) plots on five days during the 2001 growing season (Table 2).

Before mulching and mowing the two respective plots, we found a close correlation between the aboveground plant biomass and NDVI for the mown plot (Fig. 3a), while the fallow plot displayed the relatively weakest correlation (Fig. 3c) even if the differences between the correlation coefficients were statistically highly significant ($p < 0.01$) for all treatments.

On the contrary, only the fallow (Fig. 3d) and mulched (Fig. 3f) plots displayed statistically significant ($p < 0.05$) correlations between NDVI and GR before the treatments, but these correlations were weaker than those between NDVI and green biomass.

There was no statistically significant correlation between biomass and NDVI for any of the plots after their mulching or mowing. But one could notice a decrease of NDVI values for the first harvest date after applying these treatments (Fig. 2 and Fig. 4a, c, e).

The fallow plot (Fig. 4d) indicates a statistically highly significant correlation ($p < 0.01$) between NDVI and GR calculated from values of the last two sampling dates (after application of the respective treatments to the other two plots).

There were statistically significant differences ($p < 0.05$) between the GR indices for all combinations of the mulched, mown and unmanaged (fallow) plots only on the first (24 May) and the last (20 September) sampling days, except for the mulched × unmanaged combination on the latter date.

The relationships between the green biomass, litter and NDVI for each treatment are illustrated in detail in Figs. 5–7.

In the fallow plot, as expected, the values of both green plant biomass and litter were highest on the sampling dates following the treatments (mowing, mulching) applied to the other two experimental plots (Fig. 6b). The fallow grassland stand grew faster than the other two stands at the start of the growing season (Fig. 6a). We recorded the smallest accumulation of litter in the mown plot (Fig. 5a and b). Here, also, the green biomass production was lower prior to mowing the stand than it was in both the fallow and the mulched plots at the same time.

Differences between the aboveground (green) plant biomass (dry weight per m^2) in the mulched, mown and unmanaged (fallow) plots as well as those between the standing dead material and litter dry weight per m^2 are given in Tables 3 and 4, respectively.

We followed the development of the proportion between monocotyledonous and dicotyledonous plant species in the plots subjected to the three respective treatments (Fig. 8).

In the mown plot, the cover degree of dicotyledonous plants was relatively low at the start of the growing season while it was higher in both the mulched and the fallow plots. The cover degree of dicotyledonous plants increased before mowing the plots; afterwards, however, the re-growth of dicotyledonous plants was slow. On the other hand, in the mown plot the cover degree of monocotyledonous plants increased during that period.

Table 2. Significances of the differences between the NDVI values in the mulched, mown and unmanaged (fallow) plots on five days in the 2001 growing season. The respective treatments (mowing and mulching) were applied on 19.VII.2001, after the sampling operation.

Date of sampling	Mulched × mown × unmanaged[1]	Mulched × mown[2]	Mulched × unmanaged[2]	Unmanaged × mown[2]
24.V.	0.001	0.125	0.002	0.007
20.VI.	0.001	0.981	0.001	0.001
19.VII.	0.106			
16.VIII.	0.001	0.002	0.012	0.001
20.IX.	0.001	0.886	0.001	0.001

[1] Kruskal-Wallis ANOVA by rank test, [2] Mann-Whitney *U*-test.

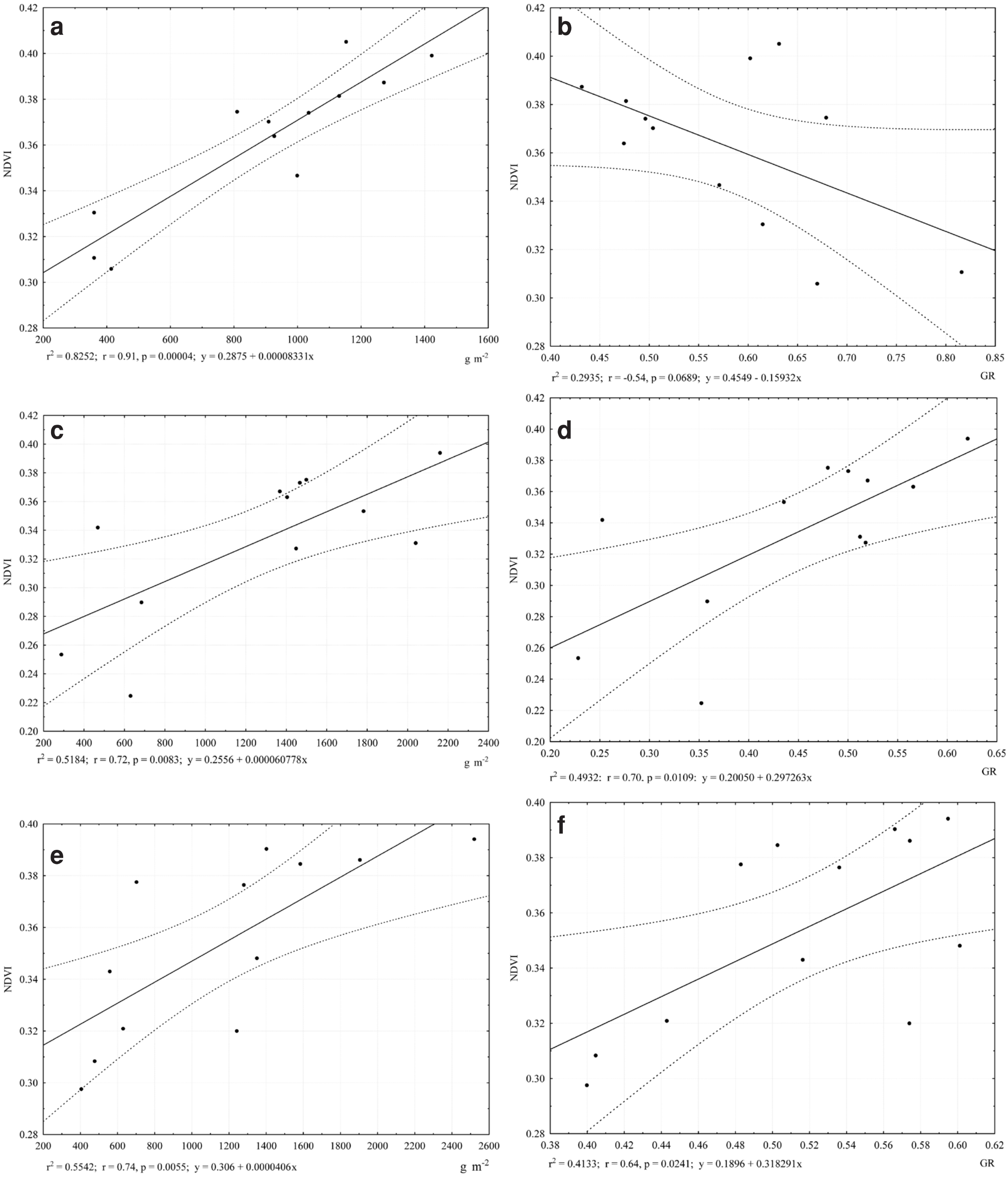

Fig. 3. Linear regressions (with 95% confidence limits) of the vegetation index (NDVI) on green aboveground plant biomass (g m^{-2} of fresh weight) and of the NDVI on GR index before the treatment of the mown and mulched plots; r^2 = coefficient of determination, r = regression coefficient, p = significance level. **a** and **b**: mown stand; **c** and **d**: unmanaged (fallow) stand; **e** and **f**: mulched stand.

In the fallow plot, the cover degree of monocotyledonous plants did not change much during the growing season; we observed a slight retreat of dicotyledonous plants only towards its end.

In the mulched plot, the cover degree of dicotyledonous plants was the highest and that of monocotyledonous plants the lowest of all three treatments compared.

We assessed, for all three treatments, the cover degree of the four most important domi-

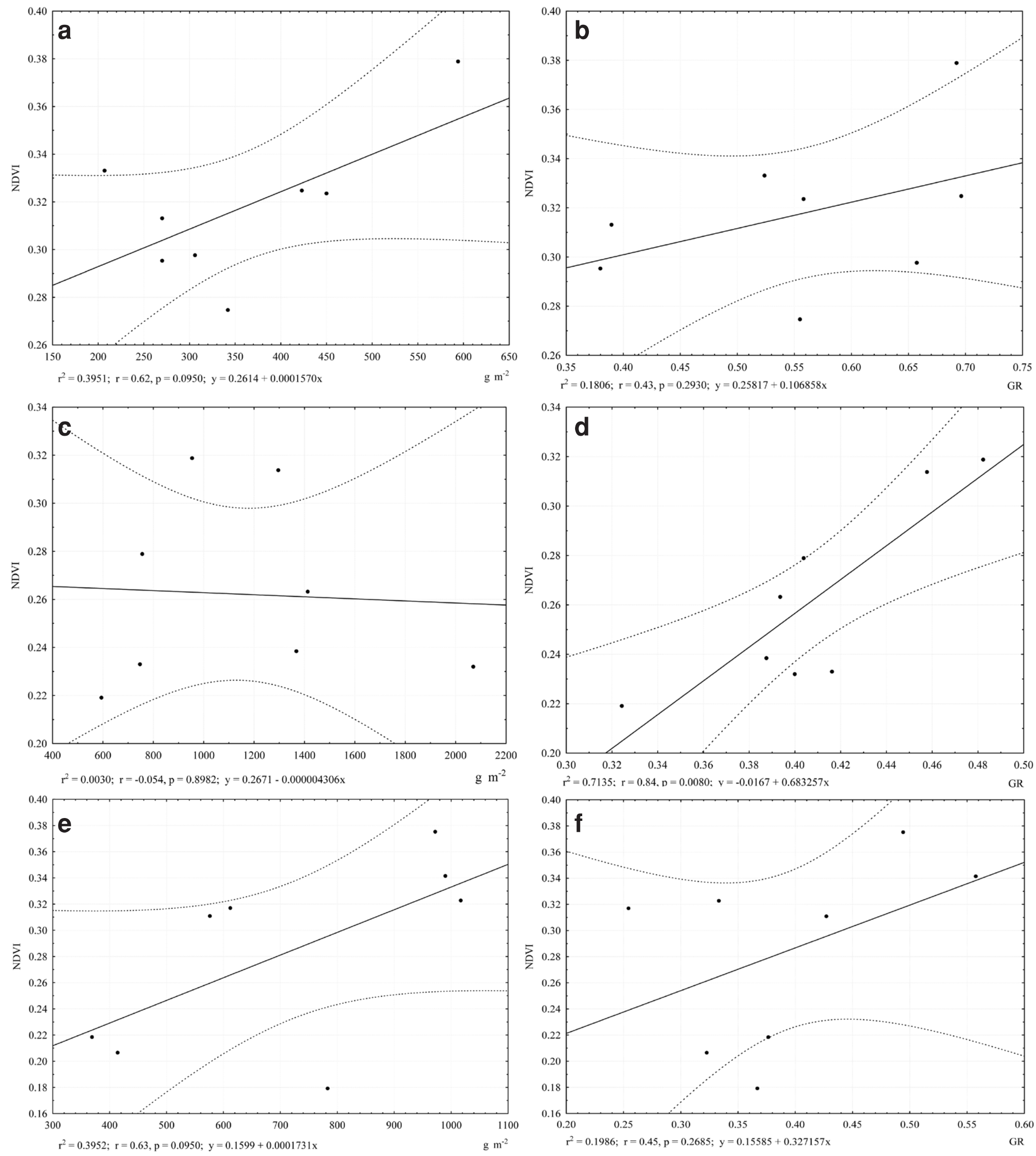

Fig. 4. Linear regressions (with 95% confidence limits) of the vegetation index (NDVI) on green aboveground plant biomass (g m^{-2} of fresh weight) and of the NDVI on GR index after the treatment of the mown and mulched plots; r^2 = coefficient of determination, r = regression coefficient, p = significance level. **a** and **b**: mown stand; **c** and **d**: unmanaged (fallow) stand; **e** and **f**: mulched stand.

nant plant species prior to mowing and mulching the respective plots (Fig. 9). The grasses *Deschampsia cespitosa* and *Festuca rubra* dominated in the mown stand. The dicotyledonous *Hypericum maculatum* dominated in the mulched stand, while the grasses *D. cespitosa, F. rubra* and *Agrostis capillaris* were represented less but almost equally. In the fallow plot, *D. cespitosa* was dominant whereas *H. maculatum* showed a lesser cover degree, comparable with that of the remaining monocotyledonous co-dominants *F. rubra* and *A. capillaris*.

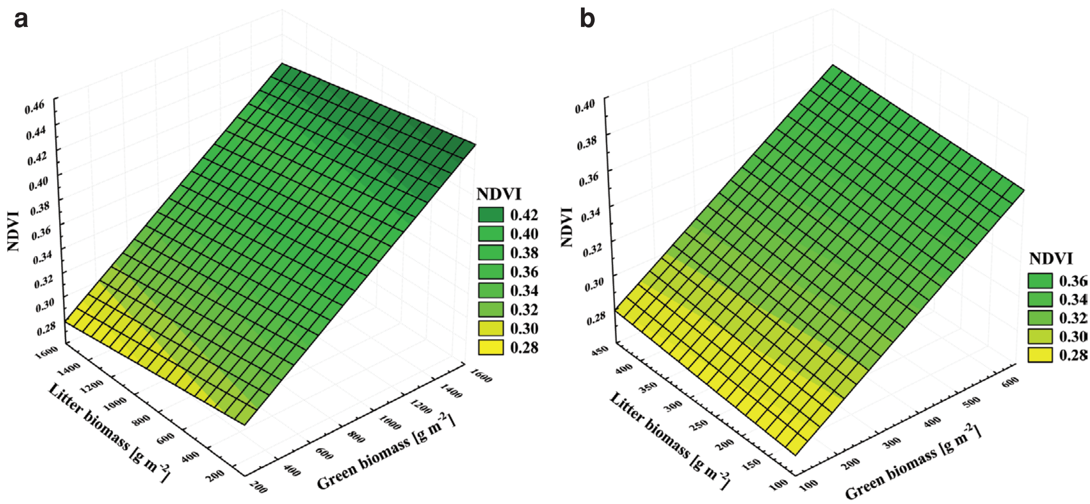

Fig. 5. Dependence of the vegetation index (NDVI) on the amounts of green aboveground plant biomass and of aboveground litter (grams of fresh weight per 1 m^2) in the mown stand (**a**) before and (**b**) after mowing on 19.VII.2001.

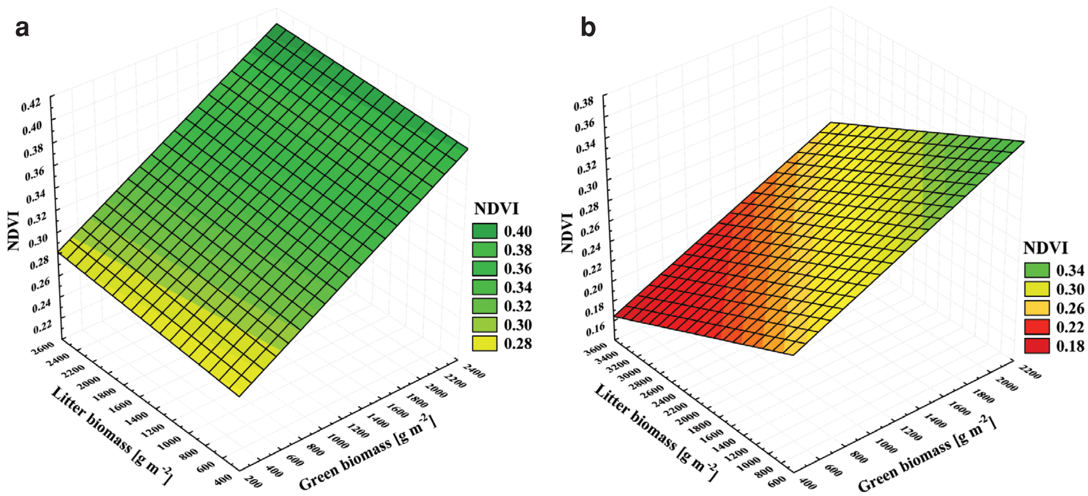

Fig. 6. Dependence of the vegetation index (NDVI) on the amounts of green aboveground plant biomass and of aboveground litter (grams of fresh weight per 1 m^2) in the unmanaged (fallow) stand (**a**) before and (**b**) after mowing or mulching the other two plots on 19.VII.2001.

Discussion

Many factors determine the NDVI response to aboveground plant biomass and/or GR index in the mountain grassland studied. When considering the first question of a correlation between the NDVI values and the amount of live aboveground biomass in the grass stands, one has to take into account the following factors and interactions between them:

- species composition of the vegetation, morphology of the dominant plant species and, particularly, the proportions of monocotyledonous (largely graminoid) and dicotyledonous (largely broad-leaved) plants in the stands;
- biomass of the vegetation as a whole and that of its constituent dominant species, again divided between different plant life and growth forms and, especially, between

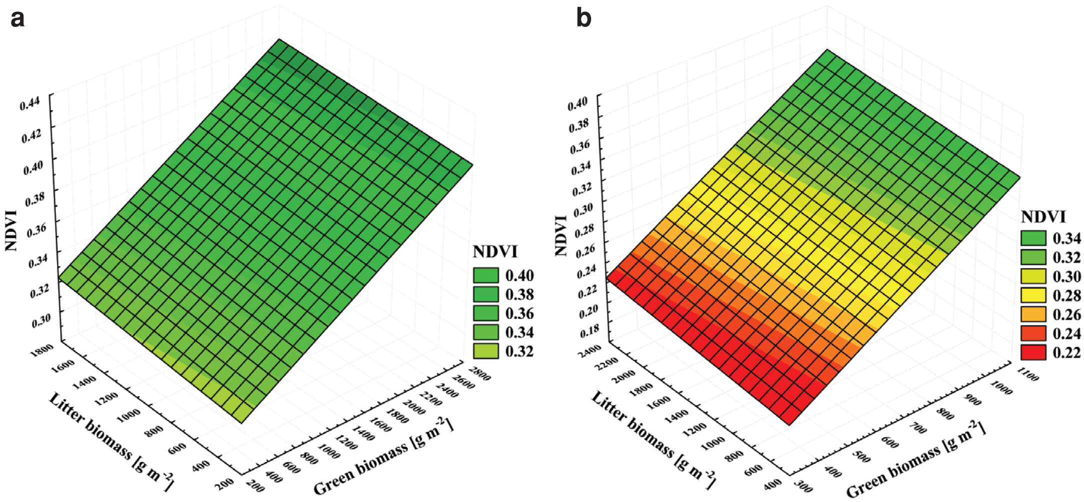

Fig. 7. Dependence of the vegetation index (NDVI) on the amounts of green aboveground biomass and aboveground litter (grams of fresh weight per 1 m^2) in the mulched stand, (**a**) before and (**b**) after its mulching on 19.VII 2001.

monocotyledonous (graminoid) and dicotyledonous plants;
- phenological phase of the vegetation at the time of the NDVI measurement;
- presence of standing dead material and litter from both the current vegetation season and the previous one.

When trying to answer the next question whether the NDVI decreases with an increasing proportion of litter, i.e., with a decreasing GR index, one has to account for the following facts:

- difference between the mulch (fresh litter) and the "natural" (dry) litter;
- penetration of live bryophytes (mosses) into the decomposing plant litter.

A correlation nevertheless exists between NDVI values and the live aboveground biomass (Figs. 3 and 4). This finding is in agreement with those of, e.g., Myneni and Williams (1994), Fuller (1998), Paruelo and Lauenroth (1998), Senay and Elliott (2000), Kawamura *et al*. (2005). Our findings showed a statistically significant linear relationship between NDVI and GR only in the unmanaged plot during the whole growing season. We could confirm, at least partly, the effect of the grassland management on the NDVI values.

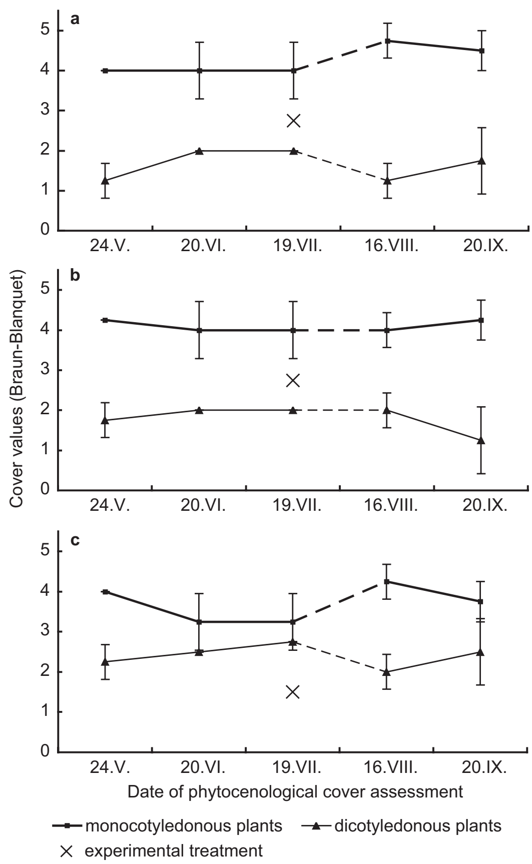

Fig. 8. Summarized cover degree values (Braun-Blanquet scale) for monocotyledonous and dicotyledonous plants in (**a**) mown, (**b**) unmanaged (fallow) and (**c**) mulched stands in 2001. Mean values and standard deviations from four replicates are given.

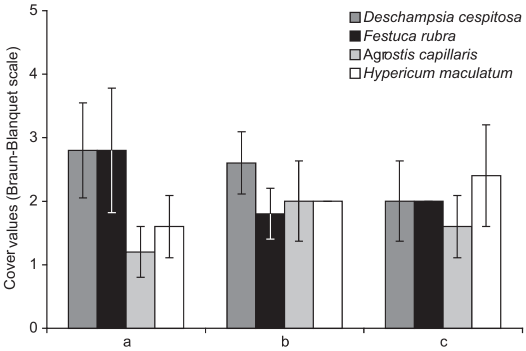

Fig. 9. Cover degree values (Braun-Blanquet scale) for four dominant species in the three respective experimental grassland stands (a: mown, b: unmanaged (fallow), c: mulched) on 18.VII.2001, i.e., one day before the **a** and **c** treatments were applied. Mean values and standard deviations from four replicates are given.

Nevertheless, Vescovo and Gianelle (2006) and Gianelle and Vescovo (2007) found the best linear relationships between GR and $NDVI_{green}$ irrespective of mountain meadow management.

Before the mowing and mulching, the three experimental mountain grassland plots displayed a similar behaviour with respect to the NDVI trends (Figs. 2, 3a, c, e), i.e., the NDVI was increasing along with the seasonal increase of aboveground (green) biomass. The unmanaged and mulched plots showed significantly higher biomass values than the mown plot (Fig. 10). The live aboveground biomass was high in the mulched plot because of faster regeneration of the vegetation at the start of the growing season, most probably thanks to natural fertilization with mineral nutrients released from the mulch, i.e., relatively nutrient-rich vegetation remains from the previous growing season (Struzina 1990). The mown plot had the lowest production of aboveground plant biomass of all three experimental plots compared. This finding is in agreement with a number of earlier studies, in which mowing without additional fertilizer application reduced the production of the vegetation (Dickinson and Polwart 1982, Willems 1983, Osbornová *et al*. 1990, Oomes *et al*. 1996).

However, in spite of the highest aboveground biomass, the NDVI values were generally lower in the unmanaged fallow plot. Early in the

Table 3. Significances of the differences between the aboveground (green) plant biomass (dry weight per m^2) in the mulched, mown and unmanaged (fallow) plots on five days in the 2001 vegetation season. The respective treatments (mowing and mulching) were applied on 19.VII.2001, after the sampling operation

Date of sampling	Mulched × mown × unmanaged[1]	Mulched × mown[2]	Mulched × unmanaged[2]	Unmanaged × mown[2]
24.V.	0.5950			
20.VI.	0.0388	0.1489	0.1489	0.0209
19.VII.	0.1548			
16.VIII.	0.0073	0.0209	0.0209	0.0209
20.IX.	0.0154	0.1489	0.0209	0.0209

[1] Kruskal-Wallis ANOVA by rank test, [2] Mann-Whitney *U*-test.

Table 4. Significances of the differences in the amounts of litter (dry weight per m^2) in the mulched, mown and unmanaged (fallow) plots on five days in the 2001 growing season. The respective treatments (mowing and mulching) were applied on 19.VII.2001, after the sampling operation.

Date of sampling	Mulched × mown × unmanaged[1]	Mulched × mown[2]	Mulched × unmanaged[2]	Unmanaged × mown[2]
24.V.	0.0073	0.0209	0.0209	0.0209
20.VI.	0.0231	0.5637	0.0209	0.0209
19.VII.	0.1738			
16.VIII.	0.0125	0.0209	0.0836	0.0209
20.IX.	0.0125	0.0209	0.0836	0.0209

[1] Kruskal-Wallis ANOVA by rank test, [2] Mann-Whitney *U*-test.

season, the differences were mainly due to the presence of significantly higher amounts of both litter and standing dead plant material largely left over from the previous year.

After the mowing and mulching, no significant correlation between the NDVI values and live aboveground plant biomass was found in any of the three experimental plots (Fig. 4a, c, e), but the regression trend is different in the fallow plot. Here, the negative slope of the regression of the NDVI on live aboveground plant biomass (Fig. 4c) documented the prevailing senescence phase of the vegetation later in the growing season. At the same time, both the mown and the mulched plots exhibited just a gentle positive slope of the above regression, with less live aboveground plant biomass than was that in the unmanaged plot. The mown plot, however, despite its lowest aboveground green biomass, showed the highest NDVI values, evidently thanks to the smallest amounts of litter within the stand. Also in the mulched plot, the NDVI sharply decreased immediately after the mulching; this was due to the fresh mulch temporarily covering the remaining green grass sward. The above results confirmed the results of e.g., van Leeuwen and Huete (1996) and Asner (1998) according to which standing dead material (and in our case also mulched litter) significantly affected the reflectance characteristics of grasslands; a small increase in standing litter can therefore have a disproportionately strong effect on canopy reflectance. The mulch, however, dried out rapidly and the grass sward soon regenerated by re-growth through the dry mulch so that the NDVI again increased — *see* also Moog *et al*. (2002) reporting a relatively fast change in the character of a grass mulch left on the spot.

Significant differences existed in the amount of standing dead material and litter between the treatments (Table 4 and Fig. 10). It can be expected that their amount increases both after mulching and when leaving senescent biomass in place. But the effect of the amount of standing dead material and litter on the NDVI values was largely non-significant (Figs. 6 and 7). The presence of bryophytes in the litter samples could result in artefacts in the form of values indicating a highly improbable increase in the "litter" amount for periods of a relatively high rate of litter decomposition. The penetration of mosses into the litter layer was, moreover, irregular in all three experimental plots: the share of mosses was the highest in the mown plot with very little litter and no standing dead plant material. The plots contained: mown 26% ± 8% (mean ± SD) of bryophytes in total dry weight of litter, unmanaged 11% ± 2%, mulched 15% ± 12%, sampling date 20 June 2001. In absolute terms (g m^{-2}) the amounts of mosses differed relatively little among the three experimental plots compared. It was unfortunately technically impracticable to separate the bryophytes from the litter they were penetrating. One may assume, however, that the presence of mosses affected only little the NDVI values, especially in the mulched and fallow plots.

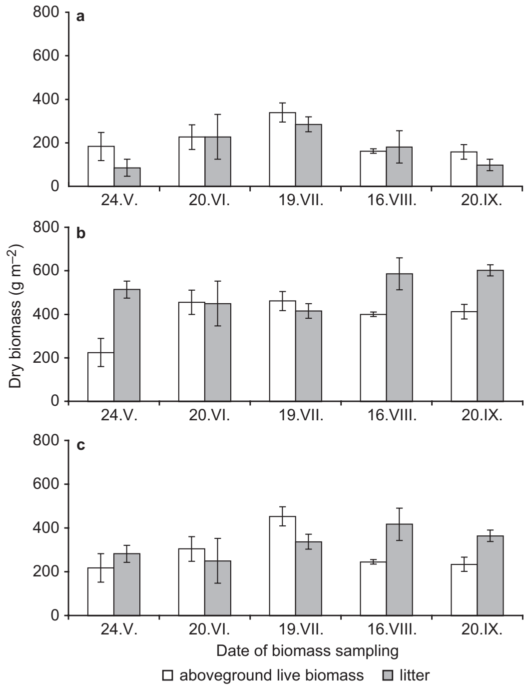

Fig. 10. Aboveground live biomass and litter (grams of fresh weight per 1 m^2) in (**a**) mown, (**b**) unmanaged (fallow) and (**c**) mulched stands in 2001. Mean values and standard deviations from four replicates are given. The date of experimental treatment is 19.VII. (after the biomass sampling).

This paper does not deal with the effects of different treatments on the species diversity of the mountain meadow vegetation. Yet, one can make a few comments on changes in the species composition of the differently managed mountain meadow plant community as a potentially important explanatory variable. Regular mowing of secondary mesophytic meadows increased their plant species diversity, especially among the dicotyledonous plant species (Bobbink and Willems 1993, Sykes *et al*. 1994, Rosén 1995, Ryser *et al*. 1995). In our experiment, however, dicotyledonous plants exhibited a lower cover degree in the mown plot than in the mulched plot (Figs. 8 and 9). This discrepancy was not due to a decline of dicotyledonous plants caused by mowing, but by prolific growth and development of the dicotyledonous dominant *Hypericum maculatum* in the mulched plot. This finding contrasted with those made by Kahmen *et al*. (2002) and Moog *et al*. (2002), who described comparable effects of equal frequencies and dates of the mowing and mulching on the species diversity of grassland vegetation. According to these authors, there is only negligible variation in the species composition of grassland vegetation regardless of leaving the biomass on the spot or removing it. Moog *et al*. (2002) assumed that the decomposition of organic matter took about four weeks under the prevailing climatic conditions, so no negative effects could be due to litter accumulation. Studies on mountain meadows, in which the decomposition was slow because of a cold climate, arrived at different conclusions. Here, the mulched plant material persisted for more than one growing season, so that its effect was amplified by its accumulation in the near-ground layer. Experimental evidence proved the mulching of mountain meadows as unsuitable, resulting in a reduced plant species diversity and in the growth and development of strongly competitive grasses and forbs such as *Deschampsia cespitosa, Hypericum maculatum* or *Holcus mollis* (Baker 1989, Hamadejová 2001, Klimeš *et al*. 2001a, 2001b, Klimeš and Květ 2001, Klimeš and Voženílková 2001; Z. Mašková unpubl. data). Leaving the mountain meadows fallow, nevertheless, led to a most pronounced decline of species diversity associated with a marked increase in the dominance of monocotyledonous plants. This finding confirms earlier ones, published by Willems (1983), Armesto and Picket (1985) and Tappeiner and Cernusca (1993), Spatz (1994), Marriot *et al*. (1996), Zelený *et al*. (2001), Laser (2002), Tasser and Tappeiner (2002).

Conclusions

Our findings stressed the importance of litter for the reflectance of the grassland canopy. The relationships between green biomass and NDVI were statistically significant for all treatments only during the period between the start and peak of the growing season, when the respective plots were mown or mulched. A statistically significant linear relationship between NDVI and GR was not detected in the mown and mulched plots even during that period. But it in the unmanaged plot this relationship was detected for the whole growing season.

The NDVI can therefore serve for detecting differences in the management of comparable grassland stands only with limitations.

Acknowledgments: We accomplished this work within the project no. VaV/620/5/97 "The Effect of Changes in Cultural Practices and Atmospheric Deposition on Biosphere Quality in Mountain and Submontane Areas of the Bohemian Forest", supported by the Ministry of Environment of the Czech Republic, and the Project no. 206/99/1410 of the Grant Agency of the Czech Republic "Functioning of Mountain Meadows under Different Management Impacts". We also acknowledge the support from the grant no. AV0Z60870520 of the Institute of Systems Biology and Ecology, Academy of Sciences of the Czech Republic and the grant no. MSM 6007665801 of the Ministry of Education of the Czech Republic.

References

Asner G.P. 1998. Biophysical and biochemical sources of variability in canopy reflectance. *Remote Sens. Environ*. 64: 234–253.

Armesto J.J. & Pickett S.T. 1985. Experiments on disturbance in old-field plant communities: impact on species richness and abundance. *Ecology* 66: 230–240.

Baker J.P. 1989. *Nature management by grazing and cutting*. Kluwer, Dordrecht.

Barbosa H.A., Huete A.R. & Baethgen W.E. 2006. A 20-year study of NDVI variability over the Northeast Region of Brazil. *J. Arid Environ*. 67: 288–307.

Baret F. & Guyot G. 1991. Potentials and limits of vegetation indices for LAI and APAR assessment. *Remote Sens. Environ*. 35: 161–173.

Bobbink R. & Willems J.H. 1993. Restoration management of abandoned chalk grassland in the Netherlands. *Biodiv. Conserv*. 2: 616–626.

Braun-Blanquet J. 1964: *Pflanzensoziologie*, ed. 3. Springer-Verlag, Vienna and New York.

Broge N.H. & Leblanc E. 2001. Comparing prediction power and stability of broadband and hyperspectral vegetation indices for estimation of green leaf area index and canopy chlorophyll density. *Remote Sens. Environ.* 76: 156–172.

Dickinson N.M. & Polwart A. 1982. The effect of mowing regime on an amenity grassland ecosystem: above- and below-ground components. *J. Appl. Ecol.* 19: 569–577.

Eklundh L. 1996. *AVHRR NDVI for monitoring and mapping of vegetation and drought in East African environments*. Ph.D. thesis, University of Lund, Lund.

Elwadie E.M., Pierce F.J. & Qi J. 2005. Remote sensing of canopy dynamics and biophysical variables estimation of corn in Michigan. *Argon. J.* 97: 99–105.

Fuller D.O. 1998. Trends in NDVI time-series and their relation to rangeland and crop production in Senegal, 1987–1993. *Int. J. Remote Sens.* 19: 2013–2018.

Gianelle D. & Vescovo L. 2007. Determination of green herbage ratio in grasslands using spectral reflectance. Methods and ground measurements. *Int. J. Remote Sens.* 28: 931–942.

Gobron N., Pinty B. & Verstraete M. 1997. Theoretical limits to the estimation of the leaf area index on the basis of visible and near-infrared remote sensing data. *IEEE Transactions on Geoscience and Remote Sensing* 35: 1438–1445.

Gopal S., Woodcock C.E. & Strahler A.H. 1999. Fuzzy neural network classification of global land cover from a 1° AVHRR Data Set. *Remote Sens. Environ.* 67: 230–243.

Haboudane D., Miller J.R., Pattey E., Zarco-Tejada P.J. & Strachan I.B. 2004. Hyperspectral vegetation indices and novel algorithms for predicting green LAI of crop canopies: modeling and validation in the context of precision agriculture. *Remote Sens. Environ.* 90: 337–352.

Hamadejová L. 2001. *Harmonisation of the production and non-production functions of meadows with Phalaroides arundinacea (L.) Rauschert*. Ph.D. thesis, Univ. of South Bohemia, Faculty of Agriculture. [In Czech with English summary].

Heinold S. 2000. *BRIV32 Software*. Dycam Inc., Chatworth, CA, USA.

Huete A., Didan K., Miura T., Rodriguez E.P., Gao X. & Ferreira L.G. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.* 83: 195–213.

Hughes M.G., Tocco P., McGarrity C., Stanker D., Singer J. & Lee D.L. 2000. Tools for delivering wide-area integrated crop management (ICM) on small New Jersey farms. In: *Proceedings of the Second International Geospatial Information in Agriculture and Forestry Conference, Lake Buena Vista, FL,USA, Jan. 10–12.2000, FL, USA*, Rutgers University, pp. 1–5.

Kahmen S., Poschlod P. & Schreiber K.-F. 2002. Conservation management of calcareous grasslands. Changes in plant species composition and response of functional traits during 25 years. *Biological Conservation* 104: 319–328.

Kawamura K., Akiyama T., Yokota H.-O., Tsutsumi M., Yasuda T., Watanabe O. & Wang S. 2005. Quantifying grazing intensities using geographic information systems and satellite remote sensing in the Xilingol steppe region, Inner Mongolia, China. *Agric. Ecosyst. Environ.* 107: 83–93.

Klimeš F. & Květ J. 2001. Phytocenological relationships in extensive pastures. *Silva Gabreta* 7: 137–140.

Klimeš F. & Voženílková B. 2001. Dynamics of species richness of extensive pastures in different zones of landscape relief. *Grassland Science in Europe* 6: 324–326.

Klimeš F., Kobes M. & Graman J. 2001a. The importance of intensive pastures in the foothills of the Bohemian Forest. *Collection of Scientiffic Papers, Faculty of Agriculture in České Budějovice, Series for Crop Sciences* 18: 83–90. [in Czech with English summary].

Klimeš F., Střeleček F., Čermák B., Hrabě F. & Tetter M. 2001b. Methodological aspects in the study of species richness and diversity in species of grasslands. *Collection of Scientific Papers, Faculty of Agriculture in České Budějovice, Series for Crop Sciences* 18: 91–98.

Koide M., Purevdorj T. & Yokoyama R. 1998. AVHRR data correction for observing NDVI in a Mongolian highland. In: Sigh R.B. & Murai S. (eds.), *Space informatics for sustainable development*, A. A. Balkema, Netherlands, pp. 107–114.

Kubát K., Hrouda L., Chrtek J.Jr., Kaplan Z., Kirschner J. & Štěpánek J. (eds.) 2002. *Klič ke květeně České republiky*. Academia, Praha.

Kvítek T., Peterková J. & Duffková R. 2001. Agrochemical properties of soil in Zhůří enclave. *Silva Gabreta* 7: 109–118.

Laser H. 2002. Long-term and short-term effects of undisturbed plant succession, mulching and meadow utilisation on the botanical diversity in a moist Arrhenatherion elatioris. *Grasslland Science in Europe* 7: 806–807.

le Maire G., Francois C. & Dufrene E. 2004. Towards universal broad leaf chlorophyll indices using PROSPECT simulated database and hyperspectral reflectance measurements. *Remote Sens. Environ.* 89: 1–28.

Lu D. 2006. The potential and challenge of remote sensing-based biomass estimation. *Int. J. Remote Sens.* 27: 1297–1328.

Marriot C.A., Bolton G.R., Common T.G., Small J.L. & Barthram G.T. 1996. Effects of extensification of sheep grazing systems on animal production and species composition of the sward. *Grassland Science in Europe* 4: 465–468.

Mašková Z., Květ J., Zemek F. & Heřman M. 2001a. Functioning of mountain meadows under different management impact — research project. *Silva Gabreta* 7: 5–14.

Mašková Z., Zemek F., Heřman M. & Květ J. 2001b. Post World War II development and present state of nonforested area at Zhůří-Huťská hora Mt. *Silva Gabreta* 7: 15–30.

McDonald A.J., Gemmell F.M. & Lewis P.E. 1998. Investigation of the utility of spectral vegetation indices for determining information on coniferous forests. *Remote Sens. Environ.* 66: 250–272.

McVicar T.R. & Jupp D.L.B. 1998. The current and potential operational uses of remote sensing to aid decisions on drought exceptional circumstances in Australia: a review. *Agr. Syst.* 57: 399–468.

Moog D., Poschlod P., Kahmen S. & Schreiber K.-F. 2002. Comparison of species composition between different grassland management treatments after 25 years. *Appl. Veg. Sci.* 5: 99–106.

Moran M.S., Inoue Y. & Barnes E.M. 1997. Opportunities and limitations for image-based remote sensing in precision crop management. *Remote Sens. Environ.* 61: 319–346.

Moravec J. 1965. *Wiesen im mittleren Teil des Böhmerwaldes (Šumava).*— Vegetace ČSSR A1 Academia, Praha.

Mutanga O. & Skidmore A.K. 2004. Narrow band vegetation indices overcome the saturation problem in biomass estimation. *Int. J. Remote Sens.* 25: 3999–4014.

Myneni R.B. & Williams D.L. 1994. On the relationship between FAPAR and NDVI. *Remote Sens. Environ.* 49: 200–211.

Nagler P., Glenn E. & Huete A. 2001. Assessment of vegetation indices for riparian vegetation in the Colorado River Delta, Mexico. *J. Arid Environ.* 49: 91–110.

Nagler P., Glenn E., Thompson L. & Huete A. 2004. Leaf area index and normalized difference vegetation index as predictors of canopy characteristics and light interception by riparian species on the Lower Colorado River. *Agricultural and Forest Meteorology* 125: 1–17.

North P.R.J. 2002. Estimation of fAPAR, LAI, and vegetation fractional cover from ATSR-2 imagery. *Remote Sens. Environ.* 80: 114–121.

Oomes M.J.M., Olff H. & Altena H.J. 1996. Effects of vegetation management and raising the water table on nutrient dynamics and vegetation change in a wet grassland. *J. Appl. Ecol.* 33: 576–588.

Osbornová J., Kovářová M., Lepš J. & Prach K. 1990. *Succession in abandoned fields. Studies in Central Bohemia, Czechoslovakia.* Kluwer, Dordrecht.

Paruelo J.M. & Lauenroth W.K. 1998. Interannual variability of NDVI and its relationship to climate for North American shrublands and grasslands. *Journal of Biogeography* 25: 721–733.

Pettorelli N., Vik J.O., Mysterud A., Gaillard J.-M., Tucker C.J. & Stenseth N.C. 2005. Using the satellite-derived NDVI to assess ecological responses to environmental change. *Trends in Ecology & Evolution* 20: 503–510.

Rosén E. 1995. Periodic droughts and long-term dynamics of Alvar grassland vegetation on Öland, Sweden. *Folia Geobot. Phytotax.* 30: 131–140.

Rouse J.W., Haas R.H., Schell J.A. & Deering D.W. 1974. Monitoring vegetation systems in the Great Plains with ERTS. In: Fraden S.C., Marcanti E.P. & Becker M.A. (eds.), *Third ERTS-1 Symposium, 10–14 Dec. 1973*, NASA SP-351, Washington D.C. NASA, pp. 309–317.

Ryser P., Langenauer R. & Gigon O. 1995. Species richness and vegetation structure in a limestone grassland after 15 years management with six biomass removal regimes. *Folia Geobot. Phytotax.* 30: 157–167.

Scurlock J.M.O., Asner G.P. & Gower S.T. 2001. *Worldwide historical estimates and bibliography of leaf area index, 1932–2000.* ORNL Technical Memorandum TM–2001/268, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Senay G.B. & Elliott R.L. 2000. Combining AVHRR-NDVI and landuse data to describe temporal and spatial dynamics of vegetation. *For. Ecol. Manage.* 128: 83–91.

Spatz G. 1994. *Freiflächenpflege.* Ulmer, Stuttgart.

Struzina A. 1990. *The effect of mulch on soil physical factors affecting plant growth.* Ph.D. thesis, Forschungsbericht Agrartechnik des Arbeitskreises Forschung und Lehre der Max-Eyth-Gesellschaft (MEG), Bonn. [In German with English summary].

Sykes M.T., van der Maarel E., Peet R.K. & Willems J.H. 1994. High species mobility in species-rich plant communities: An intercontinental comparison. *Folia Geobot. Phytotax.* 29: 439–448.

Tappeiner U. & Cernusca A. 1993. Alpine meadows and pastures after abandonment. Results of the Austrian MaB-programme and the EC-STEP project INTEGRALP. *Pirineos* 141–142: 97–118.

Tasser E. & Tappeiner U. 2002. Impact of land use changes on mountain vegetation. *Appl. Veg. Sci.* 5: 173–184.

Telesca L., Lasaponara R. & Lanorte A. 2006. 1/fα fluctuations in the time dynamics of Mediterranean forest ecosystems by using normalized difference vegetation index satellite data. *Physica A: Statistical Mechanics and its Applications* 361: 699–706.

Tucker C.J. 1980. Remote sensing of leaf water content in the near infrared. *Remote Sens. Environ.* 10: 23–32.

van Leeuwen W.J.D. & Huete A.R. 1996. Effects of standing litter on the biophysical interpretation of plant canopies with spectral indices. *Remote Sens. Environ.* 55: 123–138.

Vescovo L. & Gianelle D. 2006. Mapping the green herbage ratio of grasslands using both aerial and satellite-derived spectral reflectance. *Agric. Ecosyst. Environ.* 155: 141–149.

White M.A., Asner G.P., Nemani R.R., Privette J.L. & Running S.W. 2000. Measuring fractional cover and leaf area index in arid ecosystems: digital camera, radiation transmittance, and laser altimetry methods. *Remote Sens. Environ.* 74: 45–57.

Willems J.H. 1983. Species composition and above ground phytomass in chalk grassland with different management. *Vegetatio* 52: 171–180.

Zarco-Tejada P.J., Miller J.R., Mohammed G.H., Noland T.L. & Sampson P.H. 2001. Estimation of chlorophyll fluorescence under natural illumination from hyperspectral data. *International Journal of Applied Earth Observation and Geoinformation* 3: 321–327.

Zhang X., Friedl M.A., Schaaf C.B., Strahler A.H., Hodges J.C.F., Gao F., Reed B.C. & Huete A. 2003. Monitoring vegetation phenology using MODIS. *Remote Sens. Environ.* 84: 471–475.

Zheng D., Rademacher J., Chen J., Crow T., Bresee M., Le Moine J. & Ryu S.-R. 2004. Estimating aboveground biomass using Landsat 7 ETM+ data across a managed landscape in northern Wisconsin, USA. *Remote Sens. Environ.* 93: 402–411.

Zelený D., Šraitová D., Mašková Z. & Květ J. 2001. Management effects on a mountain meadow plant community. *Silva Gabreta* 7: 45–54.