

## **Assessment of Hyperspectral Remote Sensing for Analyzing the Impact of Human Trampling on Alpine Swards**

Authors: Kycko, Marlena, Zagajewski, Bogdan, Zwijacz-Kozica, Magdalena, Cierniewski, Jerzy, Romanowska, Elżbieta, et al.

Source: Mountain Research and Development, 37(1) : 66-74

Published By: International Mountain Society

URL: <https://doi.org/10.1659/MRD-JOURNAL-D-15-00050.1>

---

BioOne Complete ([complete.BioOne.org](https://complete.BioOne.org)) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at [www.bioone.org/terms-of-use](https://www.bioone.org/terms-of-use).

Usage of BioOne Complete content is strictly limited to personal, educational, and non-commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

---

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

# Assessment of Hyperspectral Remote Sensing for Analyzing the Impact of Human Trampling on Alpine Swards

Marlena Kycko<sup>1\*</sup>, Bogdan Zagajewski<sup>1</sup>, Magdalena Zwijacz-Kozica<sup>2</sup>, Jerzy Cierniewski<sup>3</sup>, Elżbieta Romanowska<sup>4</sup>, Karolina Orłowska<sup>1,5</sup>, Adrian Ochtyra<sup>1,5</sup>, and Anna Jarocińska<sup>1</sup>

\* Corresponding author: marlenakycko@uw.edu.pl

<sup>1</sup> Department of Geoinformatics, Cartography and Remote Sensing, University of Warsaw, Krakowskie Przedmieście 30, 00-325, Warsaw, Poland

<sup>2</sup> Tatra National Park, Kuźnice 1, 34-500, Zakopane, Poland

<sup>3</sup> Department of Soil Science and Remote Sensing of Soils, Adam Mickiewicz University, Długa 27, 61-680, Poznań, Poland

<sup>4</sup> University of Warsaw, Faculty of Biology, Department of Molecular Plant Physiology, Młeczniakowa 1, 02-096, Warsaw, Poland

<sup>5</sup> University of Warsaw, College of Inter-Faculty Individual Studies in Mathematics and Natural Sciences, Al. Żwirki i Wigury 93, 02-096, Warsaw, Poland

© 2017. Kycko et al. This open access article is licensed under a Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>). Please credit the authors and the full source.



Tourist traffic has been observed to cause changes in vegetation cover, particularly in alpine areas. These changes can be monitored using remote-sensing methods.

This paper presents an analysis of the condition of the dominant sward species surrounding the most frequented alpine tourist trails in the Tatra National Park, one of the most visited natural mountain parks in Poland and a UNESCO Man and the Biosphere Reserve. Hyperspectral measurements of interactions between the electromagnetic spectrum and the morphology and physiology of plants were presented. The spectral properties of plants and remote-sensing vegetation indices could be used at

a later date for monitoring, for example from the air. The results identified the species' sensitivity and resistance to trampling and allowed an assessment of their physiological condition. Differences were observed in the conditions of trampled and control plants. The alpine swards in the Tatra National Park were assessed as being in good condition, with only small areas located close to the most popular trails showing damage. The proposed method for analyzing the condition of alpine swards could be a useful tool for the future management of protected areas.

**Keywords:** Tatra National Park; vegetation; vegetation indices; trampling; spectrometer; chlorophyll content; photosynthetically active radiation.

**Peer-reviewed:** June 2016 **Accepted:** November 2016

## Introduction

In the natural world, plants are exposed to different environmental factors, which may induce stress reactions and inhibit many physiological functions (Kreslavski et al 2007). Trampling, an example of a mechanical stress factor (Grabherr 1982; Sørensen et al 2009), causes physical damage either by applying excess flexural load or by crushing the plant organs (Sun and Liddle 1993). Several mechanical traits, including leaf toughness, root strength, and stem flexibility, play a key role in a plant's tolerance to trampling (Kobayashi et al 1999; Striker et al 2011). Although the responses of plants to other forms of mechanical stress have been documented, little is known about the reaction in the form of changes within plant cells to trampling itself.

Defoliation occurs simultaneously during trampling, and plants typically respond to this process by increasing

the allocation of water and nutrients to leaves at the expense of the roots and stems (Xu et al 2013). Trampling-induced defoliation causes direct loss of nutrients and reductions in photosynthetic surface. This makes plants more vulnerable to mechanical damage and may cause soil erosion along with a decrease in biomass. The differences in resistance are mainly a result of plant morphology (Whinam and Chilcott 1999, 2003).

Popular tourist destinations such as natural mountain parks are especially vulnerable to trampling. Trampling has a destructive influence on natural alpine vegetation (Grabherr 1982). Tourist trampling has been found to have a significant effect on the condition of alpine grasslands, particularly at the beginning of the vegetation season (Piscová et al 2011). The regeneration of plants near tourist trails is difficult, even for species that are highly resistant to trampling (Klug et al 2002). Appropriate management of tourist activities, including

hiking, plays an important role in alpine ecosystem management.

In the Tatra Mountains on the border between Poland and Slovakia, which are the focus of this study, various studies of human influence (including trampling) have been conducted and have shown that these impacts are not constant in time and intensity (Czochański and Szydarowski 2000; Pociask-Karteczka et al 2007)—for example, the impact of skiing is less intense than that of sheep grazing (Guzik 2001). In the Tatra National Park (Poland), the most significant influence of tourists occurs in the central part of the High Tatras (Gąsienicowa Valley and Kasprowy Peak) during the peak growing season.

The increasing number of tourists leads to trampling of vegetation, which causes changes in species composition of plant communities and progressive erosion of trails (Rączkowska and Kozłowska 2010). To preserve the natural environment, it is necessary to track these changes and to take protective measures. There is currently no universal and comprehensive method of plant monitoring in mountain parks. Remote-sensing methods, which are much faster and more reliable than the traditional laboratory-based spectrometry, have not yet been used for this purpose. Remote sensing methods based on spectrometry offer more reliable and precise tools to analyze the state of vegetation. Since each object absorbs and reflects different quantities of radiation, it is possible to describe its characteristics by analyzing the reflectance of the electromagnetic spectrum (Jensen 1983; Bannari et al 1995; Zagajewski et al 2005, 2006; Jarocińska and Zagajewski 2008; Kycko 2012). Research on vegetation cover was conducted by Zha et al (2003), but the spatial resolution of Landsat data does not show the heterogeneity of swards cover well. Changes may occur over a few meters, especially in high mountain areas (Asner and Lobell 2000). Researchers have also noted that grassland surfaces are highly heterogeneous, which is a challenge for remote-sensing techniques, because their reflectance can be complex (Roder et al 2007).

To detect small-scale changes in the vegetation, it is necessary to increase spatial resolution; to this end, WorldView-2 images (Wiesmair et al 2016) and hyperspectral measurements (Kycko et al 2014) have been tested. Much of the current research on vegetation condition is based on both field and airborne hyperspectral data—for example, alpine grassland research in Switzerland (Rapp et al 2013) and nonforest vegetation analysis in the Karkonosze Mountains in Poland (Jarocińska et al 2016) using APEX hyperspectral data or vegetation monitoring (Aspinall 2002; Schmidlein and Sassini 2004; Zarco-Tejada et al 2012).

Hyperspectral data allow very precise assessment of the biochemical and biophysical state of vegetation (Darvishzadeh et al 2008). Therefore, hyperspectral field measurements may serve as a source of data to calculate

remote-sensing vegetation condition indices. The indices used in this study provide information about a plant's biophysical parameters and could have multiple applications in the quantitative and qualitative analysis of mountain vegetation (Zwijacz-Kozica 2010; Zwijacz-Kozica et al 2010; Kycko et al 2012, 2014; Jarocińska 2014; Ochtyra et al 2016).

Previous information on the merits of using such methods and showing differences in the state of trampled vegetation has not determined specific, precise parameters or indicators for a large number of species. The objectives of this study were to use remote-sensing methods to determine the effect of trampling on alpine swards in mountain areas, identify species that are sensitive to trampling, and determine the most suitable vegetation indices to investigate these influences using hyperspectral measurements, which could be verified by airborne detectors in the near future. The study offers a possible method to assess the impact of trampling and thus inform decisions on sustainable management and development of protected areas.

## Study area

The Tatra Mountains are the only alpine environment in Poland and Slovakia (Paryska and Paryski 1995). The Polish part of the Tatras covers an area of 150 km<sup>2</sup>; its highest peak is Rysy at 2499 m (Klimaszewski 1988). The surveyed plant communities belong to the alpine and subalpine zones. The alpine zone in the Tatra Mountains extends from approximately 1800 to 2300 m above sea level and consists mostly of high-mountain grasslands (Paryska and Paryski 1995). The subalpine zone extends from 1500 to 1800 m above sea level and consists of mountain pine scrub as well as grazed and nongrazed grassland.

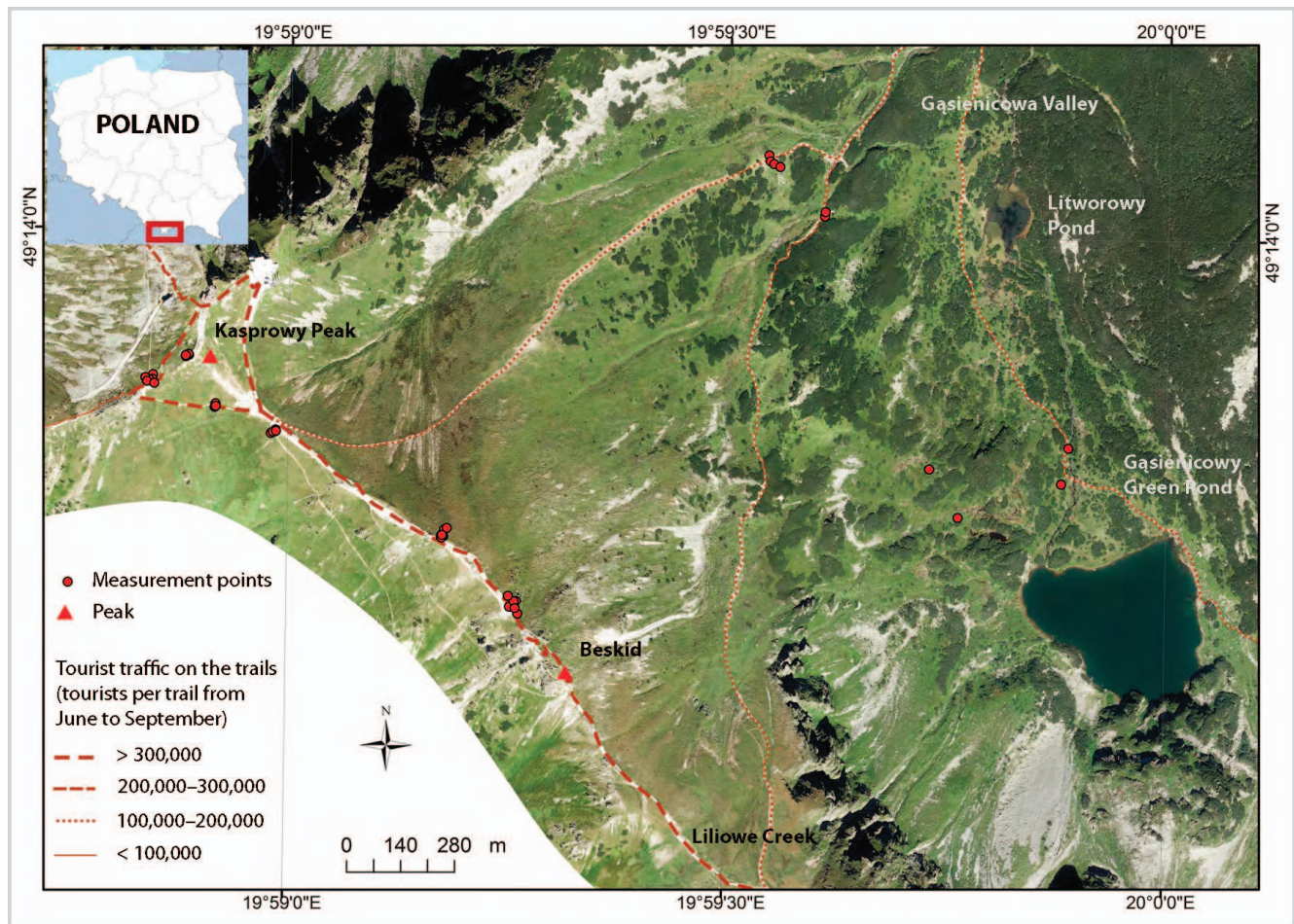
Specific study sites were selected along the Gąsienicowa Valley (Figure 1) in the central part of the Tatras, where the most intensive hiking in the Tatra National Park occurs (Skrzydłowski 2010). Thanks to its attractive location, easy accessibility, and natural values, the Gąsienicowa Valley was visited by about 1 million tourists in 2011 (almost 30% of all visitors to the Tatra National Park). In 1935–1936, a cable car line was built on top of nearby Kasprowy Peak, which intensified tourist development in this part of the Tatras (Paryska and Paryski 1995).

## Methods

Although most vegetation communities are heterogeneous, the acquired spectral response undergoes various interferences and is the averaged spectral response for many species. To obtain a spectral signal from a single species at a time, measurements were taken on highly homogeneous alpine sward areas along hiking



**FIGURE 1** The research area (using an orthophotomap from 2012, made available by the Tatra National Park). (Map by Marlena Kycko)



trails. The initial analysis of alpine sward plant communities located along the trails was conducted with a vegetation map at a scale of 1:10,000 (Kozłowska and Plit 2002; Kozłowska 2006). The following species were selected for detailed analysis: *Juncus trifidus*, *Oreochloa disticha*, *Agrostis rupestris*, *Deschampsia flexuosa*, *Festuca airoides*, *Festuca picta*, *Luzula alpinopilosa*, and *Nardus stricta*. The main criterion for selection was the dominant presence of the species.

The measurement locations were homogeneous patches of the selected species located in trampled zones (<5 m from a trail) and control areas (5–10 m from a trail). A distance of 5 m is considered the maximum that tourists are likely to walk away from the trail, because of the steepness of the slope. The highest number of test polygons were along the trail from the Kasprowy Peak to the Beskid Peaks. Others were located along the Kasprowy Peak and Gąsienicowa Valley trails and near the Gąsienicowy Green Pond (Figure 1).

### Measurements

Approximately 30 measurements for each species were acquired from each test polygon. The field measurements were conducted from 17 to 21 August 2011 when weather conditions were stable (Figure 2), with the following data collected:

- Spectrometric measurements were carried out using a field spectrometer (ASD FieldSpec 3) operating in the range from 350 to 2500 nm. The measurements were preceded by spectrometer optimization and calibration. Each measurement was performed only on plant leaves using the ASD PlantProbe. Each type of plant was analyzed with 30 averaged measurements (1 spectral measurement was averaged from 30 independent reflectance samples; Kycko et al 2013).
- The total content of chlorophyll—the principal pigment responsible for the light energy absorption required for photosynthesis and plant growth—was measured with a CCM-200 chlorophyll meter.

**FIGURE 2** The first 2 authors of the present article conducting field measurements in the Gąsienicowa Valley. (Photo by Magdalena Oprządek)



- Photosynthetically active radiation (PAR)—the expression of a plant's energy storage capacity—was sampled on dense vegetation cover using the AccuPAR ceptometer. The fraction of absorbed PAR (fAPAR) operates between 400–700 nm and describes energy, mass, and momentum exchanges between the canopy and the atmosphere, and productivity of plant cells. The fAPAR was calculated as follows:

$$fAPAR = (PAR_o + PAR_s - PAR_t - PAR_c) / PAR_o$$

where  $PAR_o$  = total incoming radiation,  $PAR_s$  = soil-reflected PAR,  $PAR_t$  = PAR transmitted through the canopy, and  $PAR_c$  = canopy-reflected PAR (Weiss and Baret 2011).

### Analysis

Calculation of vegetation indices was based on the spectral characteristics of the selected species. The differences between the reflectance of plants located near the trails (0–5 m) and in the control sites (5–10 m from trails) were analyzed by calculating the vegetation indices from 7 different groups. The 7 groups of indices (calculated based on spectrometer measurements) describe different plant parameters such as chlorophyll or nitrogen and water content. One additional bioradiometric group is based on the Chlorophyll Content Index (CCI) and fAPAR, which were used to verify the information acquired with the spectrometer (Table 1).

All statistical analyses were performed with the STATISTICA 12 software based on 23 testing areas near the trails and 25 control areas. In each measured area and for each species, spectral characteristics and chlorophyll content were measured 30 times for species. fAPAR was measured only 3 times in each research area, because the dense vegetation cover and the weather conditions did

not change much. For each species, the average spectral reflectance of trampled and control vegetation patches was compared. Statistically significant differences between polygons were evaluated with a 1-way analysis of variance (ANOVA) at 3 levels of significance (0.05, 0.01, and 0.001). The ANOVA of reflectance and remote-sensing vegetation indices compared the spectra of trampled and control plants. The 3 levels of statistical significance allowed us to determine the maximum acceptable probability of type I error, which determines the maximum acceptable risk of error. In sum, we tried to determine, to an accuracy of 95%, 99%, and 99.9%, which species and what part of the spectrum ranges and remote sensing vegetation indices showed the differences between the control and trampled areas.

For additional analysis, the remote-sensing vegetation indices were correlated with the values of biophysical variables (CCI and fAPAR) using the Pearson product-moment correlation coefficient ( $R$ ), a measure of the strength and direction of the linear relationship between 2 variables. The verification of the actual use of light in photosynthesis was conducted using fAPAR.

### Results

The remote-sensing indices derived from the hyperspectral measurements confirmed different levels of plant resistance to trampling, water stress, and limitations of PAR absorption. (The indices and their abbreviations are listed in Table 1.) Most statistically significant changes could be observed in chlorophyll content (CCI), cell structure (Normalized Difference Vegetation Index [NDVI], Atmospherically Resistant Vegetation Index [ARVI], Modified Red Edge Simple Ratio Index [mSR<sub>705</sub>], and Modified Red Edge Normalized Difference Vegetation Index [mNDVI<sub>705</sub>]), and water content in leaves (Water Band Index [WBI] and Normalized Difference Water Index [NDWI]). These differences were observed in over 87.5% of the analyzed patches ( $P < 0.001$ ). Changes were visible in the absorption of PAR (50–62.5% of all measured cases of Structure-Insensitive Pigment Index (SIPI) and Photochemical Reflectance Index (PRI),  $P < 0.001$ ). The total amount of carbon (dry mass of the cellulose and lignin; eg Cellulose Absorption Index [CAI] and Plant Senescence Reflectance Index [PSRI]) showed statistically significant changes in 62.5% of all measured cases (*Supplemental material*, Table S1: <http://dx.doi.org/10.1659/MRDJOURNAL-D-15-00050.S1>).

*A. rupestris* and *O. disticha* were the most susceptible to trampling: 30 independent measurements showed significant differences (95.8–100% of the analyzed polygons at  $P < 0.05$ ; 79.2–91.7% of the analyzed polygons at  $P < 0.001$ ). *N. stricta* was impacted by trampling in only 41.7% of the polygons near the trails. *J. trifidus* was impacted by trampling to a lesser degree, with only 37.5% of observations for a statistical significance level  $P <$



TABLE 1 Remote-sensing vegetation indices.

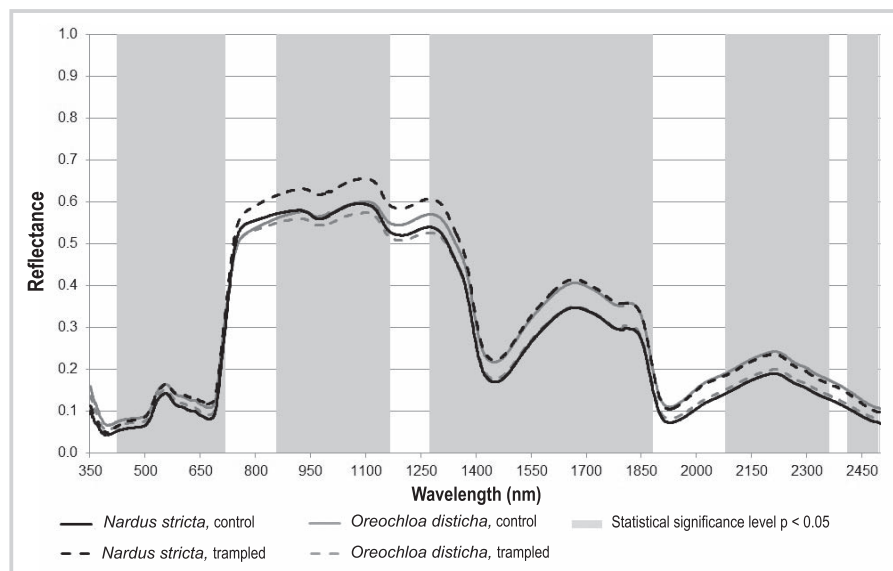
Groups of indices	Abbreviation	Index name	Citation
Broadband greenness	NDVI <sup>a)</sup>	Normalized Difference Vegetation Index	Rouse et al 1973
	SR <sup>a)</sup>	Simple Ratio Index	Rouse et al 1973
	EVI <sup>a)</sup>	Enhanced Vegetation Index	Huete et al 1997
	ARVI <sup>a)</sup>	Atmospherically Resistant Vegetation Index	Kaufman and Tanre 1992
Narrowband greenness	NDVI <sub>705</sub>	Red Edge Normalized Difference Vegetation Index	Gitelson and Merzlyak 1994
	mSR <sub>705</sub>	Modified Red Edge Simple Ratio Index	Datt 1999
	mNDVI <sub>705</sub>	Modified Red Edge Normalized Difference Vegetation Index	Datt 1999
	VOG1	Vogelmann Red Edge Index 1	Vogelmann et al 1993
	VOG2	Vogelmann Red Edge Index 2	Vogelmann et al 1993
	VOG3	Vogelmann Red Edge Index 3	Vogelmann et al 1993
Light use efficiency	PRI	Photochemical Reflectance Index	Gamon et al 1992
	SIPI	Structure Insensitive Pigment Index	Peñuelas et al 1995
Canopy nitrogen	NDNI	Normalized Difference Nitrogen Index	Fourty et al 1996
Dry or senescent carbon	NDLI	Normalized Difference Lignin Index	Fourty et al 1996
	CAI	Cellulose Absorption Index	Nagler et al 2003
	PSRI	Plant Senescence Reflectance Index	Merzlyak et al 1999
Leaf pigments	CRI1	Carotenoid Reflectance Index 1	Gitelson et al 2002
	CRI2	Carotenoid Reflectance Index 2	Gitelson et al 2002
	ARI1	Anthocyanin Reflectance Index 1	Gitelson et al 2001
	ARI2	Anthocyanin Reflectance Index 2	Gitelson et al 2001
Canopy water content	WBI	Water Band Index	Peñuelas et al 1995
	NDWI	Normalized Difference Water Index	Gao 1996
	MSI	Moisture Stress Index	Rock et al 1985
	NDII	Normalized Difference Infrared Index	Hardisky et al 1983
Bioradiometric index	CCI	Chlorophyll Content Index	Campbell et al 1990
	fAPAR	Fraction of absorbed photosynthetically active radiation	Moneith 1977

<sup>a)</sup>To implement these data in multispectral hyperspectral indices, we used the following ranges of wavelength bands: for red, 600–700 nm; for green, 500–600 nm; for blue, 400–500 nm; for NIR, 760–960 nm.

0.001. *N. stricta* and *J. trifidus* were most resistant to trampling. All other species were sensitive to trampling, but the trampling-related changes could be observed in different spectral characteristics (*Supplemental material*, Table S2: <http://dx.doi.org/10.1659/MRDJOURNAL-D-15-00050.S1>). A hierarchical classification of species vulnerability was established based on the vegetation index values in both the trampled and control areas. The highest fragility occurred in *O. disticha*.

ANOVA was performed on all individual measurements, that is, on all spectral reflectance curves. We compared ranges of the spectrum that showed a statistically significant difference for the species between the trampled and control sites. Figure 3 compares *O. disticha*, the most sensitive species, and *N. stricta*, which did not present significant differences between trampled and control areas. The spectral properties of *O. disticha* confirmed that most shortwave infrared ranges are sensitive to water content, lignin, and cellulose content in

**FIGURE 3** Spectral characteristics of *Nardus stricta* and *Oreochloa disticha* acquired at the statistical significance level of 0.05 in the trampled and control areas. Ranges marked in gray denote statistically significant differences between the control and trampled groups.



leaves (depicted by gray areas in Figure 3). Changes were also observed in wavelengths of 650 nm and 650–750 nm (red edge), the ranges responsible for the absorption of photons by chlorophyll (indicating general stress of vegetation), and in the ranges 850–1160 nm, 1270–1880 nm, 2078–2360 nm, and 2410–2496 nm.

All index values were correlated with the CCI and fAPAR indices, measuring chlorophyll content and energy accumulated by plants. A review of the condition of the alpine swards species in general, for trampled and control areas, was performed using the correlation coefficients (*R*; Table 2). The CCI and NDVI of the trampled areas oscillated around  $R = 0.57$  ( $n = 30, P < 0.05$ ). The CCI correlated in the same way for trampled plants with the

CAI ( $R = -0.65$ ), which means that when there is less chlorophyll in a plant, there is a greater quantity of dry biomass as defined by cellulose. Control plants also showed a high correlation between the CCI and CAI ( $R = -0.67$ ). The energy accumulated by plants (fAPAR) showed a strong correlation with the general condition (Red Edge Normalized Difference Vegetation Index [NDVI<sub>705</sub>],  $R = 0.71$ ), and the same index was highly correlated with the SIPI ( $-0.55$ ) in the trampled areas, which indicates a reduced use of light in the process of photosynthesis. The use of light through photosynthesis also depends on the water content of the plant, which is confirmed by the value of correlation ( $R = 0.42$ ) for control plants.

**Discussion and conclusions**

This study shows that field spectrometer data can be used to analyze anthropogenic changes in plants, specifically those caused by tourist trampling. It also identifies vegetation indices calculated from spectral reflectance curves acquired in situ that are the most useful in monitoring damage to alpine vegetation.

The field measurements indicated that alpine swards near popular trails in the Gąsienicowa Valley and near the Kasprowy Peak were generally in good condition, which was confirmed by comparison with more distant control patches. Most of the vegetation indices for the species studied were within the optimal values. In the analysis of species’ spectral reflectance curves, values in wavelengths sensitive to pigment content, cell structure, and water absorption were analogous to those presented in the literature and within the ranges typical for plants in good condition.

**TABLE 2** Verification of chlorophyll content and energy accumulation (fAPAR) by plant index, based on correlation with indices calculated from the data derived from the spectrometer ( $n = 30, P \leq 0.05$ ).<sup>a)</sup>

Type of area	Indices	Correlation coefficient ( <i>R</i> )
Trampled plants (<5 m from trail)	CCI with NDVI	0.57
	CCI with CAI	-0.65
	fAPAR with SIPI	-0.55
	fAPAR with NDVI <sub>705</sub>	0.71
Control plants (5–10 m from trail)	CCI with SIPI	-0.36
	CCI with CAI	-0.67
	fAPAR with NDNI	0.40
	fAPAR with NDII	0.42

<sup>a)</sup> The full names of the indexes are given in Table 1.

An increase in trampling intensity has been associated with an 11% decrease in plant biomass (Grabherr 1982). Research has shown that after 30 passes (people walking through the area) the amount of biomass decreased by 2% of the original volume, and after 200 passes per annum by 27% of the original amount (Whinam and Chilcott 1999, 2003). Our analyses made it possible to identify species that showed a deterioration in physiological condition after being subjected to trampling. The species that showed the least difference between trampled and nontrampled areas in remote-sensing vegetation index values were *N. stricta*, *J. trifidus*, *F. picta* (all indices), and *A. rupestris*. The greatest differences in vegetation index values between trampled and control sites were observed in *L. alpinopilosa*, *F. airoides*, *O. disticha*, and (for some indices) *D. flexuosa*. These results may be due to differences in the morphology of the species, such as the fact that *L. alpinopilosa* has broad (about 2–3 mm) green leaves, whereas the leaves of *J. trifidus* are thin and filamentous.

In laboratory studies of alpine swards, an increase of reflectance by 10% in the visible range of the electromagnetic spectrum was found to correspond to an increase in carotenoid content (Jakomulska 1999). Pigment content in *N. stricta* reached reflectance values of 0.5–0.1 in an earlier study (Sobczak 2009), whereas in our study the values were 0.5–0.15. Decreases in midinfrared wavelength reflectance suggest a more compact cell structure. For example, *L. alpinopilosa*, with peak reflectance in the near-infrared spectral range, has a spongier structure than *J. trifidus*. An increase of reflectance by 5–10% in the midinfrared wavelength is sufficient for such conclusions to be drawn. Sobczak (2009), in a visual comparison of spectral reflectance curves of *Luzula spadicica* (synonym *L. alpinopilosa*), found that reflectance in the spectral range sensitive to cell structures had values of 0.25–0.35, whereas in our research, the values were 0.6–0.7. The reflectance of *D. flexuosa* in the spectrum describing cellular structures was 0.5–0.64 in our study and 0.35–0.44 in Sobczak's.

In the comparison of water absorption wavelengths, our findings were similar to those of previous studies and showed a dependency between water content and cell structure. Jakomulska (1999) found that tissue hydration was higher in the loose, spongy tissue of *L. spadicica* (synonym *L. alpinopilosa*; 78.9% water content in the plant tissues) than in the tight cell structure of *J. trifidus* (71.3% water content in tissues). Regarding reflectance values, the range dependent on water content for *J. trifidus* was 0.1–0.2 in Sobczak's (2009) study and 0.1–0.3 in our study.

In addition to the spectral reflectance curve analysis, remote-sensing vegetation indices were calculated. Eight groups of vegetation indices were measured, but only 3 of these were statistically significant in more than 70% of cases at a significance level of  $P < 0.001$ : the broadband greenness, narrowband greenness, and canopy water

content groups. Of these, 3 broadband greenness indices proved to be applicable in the trampling-vulnerability analysis: NDVI, ARVI, and enhanced vegetation index (EVI). The most suitable narrowband greenness indices were mSR<sub>705</sub> and mNDVI<sub>705</sub>, whereas the best indices for canopy water content were WBI, NDWI, and Normalized Difference Infrared Index [NDII]. This means that (potentially trampled) plants near the trail had significantly lower chlorophyll, water content, and overall health than the control plants.

Based on the wavelengths, the remote-sensing vegetation indices such as NDVI, soil adjusted vegetation index 2, and red edge position index (Dawson and Curan 1998) were calculated. The value of these indices depends on the amount of chlorophyll, which is a very sensitive indicator of vegetation stress. With the development of remote sensing, existing indicators are being modernized, and researchers are developing new indicators that accurately utilize particular wavelengths corresponding to the characteristics and parameters of plants, such as water, pigments, and chemical elements that build plants (Rodríguez-Pérez et al 2007). Indicators like NDVI and MSAVI 2 (the modified soil-adjusted vegetation index 2, which is a soil-adjusted vegetation index that seeks to address some of the limitations of NDVI when applied to areas with a high degree of exposed soil surface) have also been used to evaluate and monitor the impact of sheep grazing on vegetation in the Aragvi Valley in Georgia (Wiesmair et al 2016). The most-used bands for the analysis of water content and water stress are 950–970, 1150–1260, and 1520–1540 nm (Sims and Gamon 2002; Rodríguez-Pérez et al 2007), whereas in our study the statistically significant ranges were 422–716, 850–1160, 1270–1880, 2078–2360, and 2410–2496 nm.

The methods presented in this paper can be used for other monitoring studies of mountain plant species. Trampling damage, observed through remote-sensing methods, varied between species. The processes of reconstruction and regeneration of the vegetation cover are particularly difficult in mountainous terrain (because of the gradient; Wiesmair et al 2016). Although novel methods to retain fractional vegetation cover from satellite images have been developed (Li et al 2014; Wiesmair et al 2016), monitoring should always be supported by field surveys (Gintzburger and Saidi 2010). Therefore, hyperspectral data constitute a promising—and what is more, noninvasive—tool for monitoring hiking trails and mountainous areas. Remote-sensing methods are increasingly being proposed for the study, restoration, and sustainable management of the region (Akiyama and Kawamura 2007). In future studies, a focus on trampling-related morphological and physiological changes would improve the understanding of plant resistance to mechanical stress.



## ACKNOWLEDGMENTS

The authors would like to thank the Tatra National Park; the Institute of Geography and Spatial Organisation of the Polish Academy of Sciences; the Anna Pasek Foundation, which funded the scholarship for Marlena Kycko in 2012/2013; and the European Space Agency, which funded the AVerS

project (4000107684/13/NL/KML), as well as Rada Konsultacyjna ds. Studentckiego Ruchu Naukowego UW [the University of Warsaw Consultation Board for Student Research].

## REFERENCES

- Akiyama T, Kawamura K.** 2007. Grassland degradation in China: Methods of monitoring, management and restoration. *Grassland Science* 53:1–17.
- Asner GP, Lobell DB.** 2000. A biogeophysical approach for automated SWIR unmixing of soils and vegetation. *Remote Sensing of Environment* 74:99–112.
- Aspinall R.** 2002. Use of logistic regression for validation of maps of the spatial distribution of vegetation species derived from high spatial resolution hyperspectral remotely sensed data. *Ecological Modelling* 157:301–312. [http://dx.doi.org/10.1016/S0304-3800\(02\)00201-6](http://dx.doi.org/10.1016/S0304-3800(02)00201-6).
- Bannari A, Morin D, Bonn F, Huete AR.** 1995. A review of vegetation indices. *Remote Sensing Reviews* 13(1–2):95–120. <http://dx.doi.org/10.1080/02757259509532298>.
- Campbell RJ, Mobley KN, Marini RP, Pfeiffer DG.** 1990. Growing conditions alter the relationship between SPAD-501 values and apple leaf chlorophyll. *Hortscience* 25:330–331.
- Czocharński J, Szydarowski W.** 2000. Diagnoza stanu i różnicowanie przestrzenno- czasowe użytkowania szlaków turystycznych w TPN. In: Czocharński J, Borowiak D, editors. *Z badań geograficznych w Tatrach Polskich*. Gdańsk, Poland: Uniwersytet Gdański, pp 207–231.
- Darvishzadeh R, Skidmore A, Schlerf M, Atzberger C, Corsi F, Cho M.** 2008. LAI and chlorophyll estimation for a heterogeneous grassland using hyperspectral measurements. *ISPRS Journal of Photogrammetry & Remote Sensing* 63:409–426.
- Datt B.** 1999. A New reflectance index for remote sensing of chlorophyll content in higher plants: Tests using eucalyptus leaves. *Journal of Plant Physiology* 154:30–36. [http://dx.doi.org/10.1016/S0176-1617\(99\)80314-9](http://dx.doi.org/10.1016/S0176-1617(99)80314-9).
- Dawson TP, Curran PJ.** 1998. Technical note: A new technique for interpolating the reflectance red edge position. *International Journal of Remote Sensing* 11:2133–2139.
- Fourty T, Baret F, Jacquemoud S, Schmuck G, Verdebout J.** 1996. Leaf optical properties with explicit description of its biochemical composition. Direct and inverse problems. *Remote Sensing of Environment* 56:104–117. [http://dx.doi.org/10.1016/0034-4257\(95\)00234-0](http://dx.doi.org/10.1016/0034-4257(95)00234-0).
- Gamon JA, Penuelas J, Field CB.** 1992. A narrow-waveband spectral index that tracks diurnal changes in photosynthetic efficiency. *Remote Sensing of Environment* 41:35–44. [http://dx.doi.org/10.1016/0034-4257\(92\)90059-S](http://dx.doi.org/10.1016/0034-4257(92)90059-S).
- Gao BC.** 1996. NDWI - A normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sensing of Environment* 58:257–266. <http://dx.doi.org/10.1117/12.210877>.
- Gintzburger G, Saidi S.** 2010. From inventory to monitoring in semi-arid and arid rangelands. In: Squires V, editor. *Range and Animal Sciences and Resource Management*. Vol II. Oxford, United Kingdom: Encyclopedia of Life Support Systems (EOLSS), pp 237–273.
- Gitelson AA, Merzlyak MN.** 1994. Spectral reflectance changes associated with autumn senescence of *Aesculus hippocastanum* L. and *Acer platanoides* L. leaves. Spectral features and relation to chlorophyll estimation. *Journal of Plant Physiology* 143:286–292. [http://dx.doi.org/10.1016/S0176-1617\(11\)81633-0](http://dx.doi.org/10.1016/S0176-1617(11)81633-0).
- Gitelson AA, Merzlyak MN, Chivkunova OB.** 2001. Optical properties and nondestructive estimation of anthocyanin content in plant leaves. *Photochemistry and Photobiology* 71:38–45. [http://dx.doi.org/10.1562/0031-8655\(2001\)0740038OPANE02.0.CO;2](http://dx.doi.org/10.1562/0031-8655(2001)0740038OPANE02.0.CO;2).
- Gitelson AA, Zur Y, Chivkunova OB, Merzlyak MN.** 2002. Assessing carotenoid content in plant leaves with reflectance spectroscopy. *Photochemistry and Photobiology* 75:272–281. [http://dx.doi.org/10.1562/0031-8655\(2002\)075<0272:ACCIPL>2.0.CO;2](http://dx.doi.org/10.1562/0031-8655(2002)075<0272:ACCIPL>2.0.CO;2).
- Grabherr G.** 1982. The impact of trampling by tourists on a high altitudinal grassland in the Tyrolean Alps, Austria. *Vegetatio* 48:209–219. <http://dx.doi.org/10.1007/BF00055262>.
- Guzik M.** 2001. *Analiza zmian szaty roślinnej Tatr przy wykorzystaniu technik geomatycznych na przykładzie Doliny Bystrzej i Sucheje Stawiańskiej* [MSc dissertation]. Kraków, Poland: Agricultural University Fr. Hugo Kołłątaj.
- Hardisky MA, Klemas V, Smart RM.** 1983. The influences of soil salinity, growth form, and leaf moisture on the spectral reflectance of *Spartina alterniflora* canopies. *Photogrammetric Engineering and Remote Sensing* 49:77–83.
- Huete AR, Liu H, Batchily K, van Leeuwen W.** 1997. A comparison of vegetation indices over a global set of TM Images for EOS-MODIS. *Remote Sensing of Environment* 59(3):440–451. [http://dx.doi.org/10.1016/S0034-4257\(96\)00112-5](http://dx.doi.org/10.1016/S0034-4257(96)00112-5).
- Jakomulska A.** 1999. Physiology and spectral signatures of the alpine species: *Juncus trifidus*, *Luzula spadicea* and *Calamagrostis villosa*. Assessment of potential for remote identification of vegetation in high-mountain environments. In: Kotarba A, Kozłowska A, editors. *Geoecological Research in the Kasprowy Wierch Area*. Prace Geograficzne 174. Wrocław, Poland: Publisher, pp XX–XX.
- Jarocińska AM.** 2014. Radiative Transfer Model parametrization for simulating the reflectance of meadow vegetation. *Miscellanea Geographica – Regional Studies on Development* 18(2):5–9. <http://dx.doi.org/10.2478/mgrsd-2014-0001>.
- Jarocińska AM, Kacprzyk M, Marcinkowska-Ochtyra A, Ochtyra A, Zagajewski B, Meuleman K.** 2016. The application of APEX images in the assessment of the state of non-forest vegetation in the Karkonosze Mountains. *Miscellanea Geographica – Regional Studies on Development* 20(1):21–27. <http://dx.doi.org/10.1515/mgrsd-2016-0009>.
- Jarocińska AM, Zagajewski B.** 2008. Korelacje naziemnych i lotniczych teledetekcyjnych wskaźników roślinności dla zlewni Bystrzanki. *Teledetekcja Środowiska* 40: 100–124.
- Jensen JR.** 1983. Biophysical remote sensing: Review article. *Annals of the Associations of American Geographers* 73(1):111–132. <http://dx.doi.org/10.1080/01431160500486732>.
- Kaufman YJ, Tanre D.** 1992. Atmospherically resistant vegetation index (ARVI) for EOS-MODIS. *IEEE Transactions on Geoscience and Remote Sensing* 30(2):261–270. <http://dx.doi.org/10.1109/36.134076>.
- Klimaszewski M.** 1988. *Rzeźba Tatr Polskich*, Warsaw, Poland: Wydawnictwo Naukowe PWN.
- Klug B, Scharfetter-Lehr G, Scharfetter E.** 2002. Effects of trampling on vegetation above the timberline in the eastern Alps, Austria. *Arctic, Antarctic, and Alpine Research* 34(4):377–388. <http://dx.doi.org/10.2307/1552195>.
- Kobayashi Y, Kaya H, Goto K, Iwabuchi M, Araki T.** 1999. A pair of related genes with antagonistic roles in mediating flowering signals. *Science* 286:1960–1962. <http://dx.doi.org/10.1126/science.286.5446.1960>.
- Kozłowska A.** 2006. Detailed mapping of high vegetation in the Tatra Mts. *Polish Botanical Studies* 22:333–341.
- Kozłowska A, Plił J.** 2002. Mapa roślinności wysokogórskiej Tatr (od Krzyżnego do Przełęczy Kondrackiej) w skali 1:10 000 i 1:20 000. In: *Przemiany środowiska przyrodniczego Tatr*, Kraków – Zakopane, pp 197–201.
- Kreslavski VD, Carpentier R, Klimov VV, Murata N, Allakhverdiev SI.** 2007. Molecular mechanisms of stress resistance of the photosynthetic apparatus. *Membrane and Cell Biology* 1:185–205. <http://dx.doi.org/10.1134/S1990747807030014>.
- Kycko M.** 2012. *Wpływ turystyki na kondycję roślinności wzdłuż wybranych szlaków doliny gasienicowej na podstawie danych teledetekcyjnych* [MSc dissertation]. Warsaw, Poland: University of Warsaw.
- Kycko M, Zagajewski B, Kozłowska A.** 2014. Variability in spectral characteristics of trampled high-mountain grasslands. *Miscellanea Geographica – Regional Studies on Development* 18(2):10–14. <http://dx.doi.org/10.2478/mgrsd-2014-0003>.
- Kycko M, Zagajewski B, Kozłowska A, Oprządek M.** 2012. Variability of spectral characteristics of selected high-mountain plant species of Gasienicowa Valley exposed for trampling. *Teledetekcja Środowiska* 47:75–86.
- Kycko M, Zagajewski B, Podbielska K, Binkowska A.** 2013. Assessment of geometry of radiation source - plant - detector on value of the remote sensing indices. *Teledetekcja Środowiska* 49:15–26.
- Li F, Chen W, Zeng Y, Zhao Q, Wu B.** 2014. Improving estimates of grassland fractional vegetation cover based on a pixel dichotomy model: A case study in Inner Mongolia, China. *Remote Sensing* 6:4705–4722.

- Merzlyak JR, Gitelson AA, Chivkunova OB, Rakitin VY.** 1999. Non-destructive optical detection of pigment changes during leaf senescence and fruit ripening. *Physiologia Plantarum* 106:135–141. <http://dx.doi.org/10.1034/j.1399-3054.1999.106119.x>.
- Moneith JL.** 1977. Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences* 281(980):277–294. <http://dx.doi.org/10.1098/rstb.1977.0140>.
- Nagler PL, Inoue Y, Glenn EP, Russ AL, Daughtry CST.** 2003. Cellulose absorption index (CAI) to quantify mixed soil–plant litter scenes. *Remote Sensing of Environment* 87:310–325. <http://dx.doi.org/10.1016/j.rse.2003.06.001>.
- Ochtyra A, Zagajewski B, Kozłowska A, Marcinkowska-Ochtyra A, Jarocińska A.** 2016. Assessment of the Tatra National Park forests condition using decision tree method and multispectral Landsat TM satellite images. *Sylvan* 160(3):256–264.
- Paryska Z, Paryski WH.** 1995. *Wielka Encyklopedia Tatrzańska*, Poronin, Poland: Wydawnictwo Górskie.
- Peñuelas J, Baret F, Filella I.** 1995. Semi-empirical indices to assess carotenoids/chlorophyll-a ratio from leaf spectral reflectance. *Photosynthetica* 31:221–230.
- Piscová V, Kanka R, Krajčí J, Barančok P.** 2011. Short-term trampling experiments in the *Juncetum trifidi* Krajina 1933 association. *Ekológia* 30(3):322–333. [http://dx.doi.org/10.4149/ekol\\_2011\\_03\\_322](http://dx.doi.org/10.4149/ekol_2011_03_322).
- Pociask-Karteczka J, Bašcik M, Czubernat S.** 2007. Ruch turystyczny w tatrzańskim Parku Narodowym w latach 1993–2005. In: Kurek W, Mika M, editors. *Studia nad turystyką. Tradycje, stan obecny i perspektywy badawcze*. Cracow, Poland: IGIgP Jagiellonian University, pp 271–279.
- Rapp M, Schweiger A, Haller R.** 2013. Biomass-mapping of alpine grassland with APEX imaging spectrometry data. In: *5th Symposium for Research in Protected Areas Conference Volume*. Location: Publisher, pp 631–638.
- Rączkowska Z, Kozłowska A.** 2010. Wpływ turystyki na rzeźbę i roślinność przy ścieżkach w otoczeniu Kasprowego Wierchu. In: Krzan Z, editor. *Nauka a zarządzanie obszarem Tatr i ich otoczeniem. T. 3. Człowiek i środowisko*. Zakopane, Poland: Tatra National Park, pp 21–28.
- Rock BN, Williams DL, Vogehmann JE.** 1985. Field and airborne spectral characterization of suspected acid deposition damage in red spruce (*Picea rubens*) from Vermont. In: *Machine Processing of Remotely Sensed Data Symposium*. Lafayette, IN: Purdue University Press, pp 71–81.
- Roder A, Kuemmerle T, Hill J, Papanastasis VP, Tsiourlis GM.** 2007. Adaptation of a grazing gradient concept to heterogeneous Mediterranean rangelands using cost surface modelling. *Ecological Modelling* 204(3–4):387–398.
- Rodríguez-Pérez JR, Riaño D, Carlisle E, Ustin SL, Smart DR.** 2007. Evaluation of hyperspectral reflectance indexes to detect grapevine water status in vineyards. *American Journal of Enology and Viticulture* 58:302–317.
- Rouse JW, Haas RH, Schell JA, Deering DW.** 1973. Monitoring vegetation systems in the Great Plains with ERTS. In: *Third ERTS Symposium*. NASA SP-351 I. Washington, DC: NASA, pp 309–317.
- Schmidtlein S, Sassini J.** 2004. Mapping of continuous floristic gradients in grasslands using hyperspectral imagery. *Remote Sensing of Environment* 92:126–138. <http://dx.doi.org/10.1016/j.rse.2004.05.004>.
- Sims DA, Gamon JA.** 2002. Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. *Remote Sensing of Environment* 81:337–354.
- Skrzydłowski T.** 2010. Zwierzęta i rośliny. In: *Przewodnik po Tatrach Polskich*. Wydawnictwo Tatrzańskiego Parku Narodowego, Zakopane. Publisher: Location: pp 17–35, 135–138, 149–152.
- Sobczak M.** 2009. Hiperspektralna metoda badania i kartowania roślinności wysokogórskiej. *Teledetekcja Środowiska* 41:79–103.
- Sørensen LI, Mikola J, Kyto MM, Olofsson J.** 2009. Trampling and spatial heterogeneity explain decomposer abundances in a sub-Arctic grassland subjected to simulated reindeer grazing. *Ecosystems* 12:830–842. <http://dx.doi.org/10.1007/s10021-009-9260-6>.
- Striker GG, Mollard FPO, Grimaldi AA, León RJC, Insausti P.** 2011. Trampling enhances the dominance of graminoids over forbs in flooded grassland mesocosms. *Applied Vegetation Science* 14:95–106. <http://dx.doi.org/10.1111/j.1654-109X.2010.01093.x>.
- Sun D, Liddle MJ.** 1993. Plant morphological characteristics and resistance to simulated trampling. *Environmental Management* 17:511–521. <http://dx.doi.org/10.1007/BF02394666>.
- Vogelmann JE, Rock BN, Moss DM.** 1993. Red edge spectral measurements from sugar maple leaves. *International Journal of Remote Sensing* 14:1563–1575. <http://dx.doi.org/10.1080/01431169308953986>.
- Weiss M, Baret F.** 2011. fAPAR (fraction of Absorbed Photosynthetically Active Radiation) estimates at various scale. In: Trinder J, editor. *34th International Symposium on Remote Sensing of Environment: The GEOSS Era: Towards Operational Environmental Monitoring*. Sydney, Australia, 10–15 April 2010, pp 1–4. <http://www.isprs.org/proceedings/2011/isrse-34/211104015Final00926.pdf>; accessed on 30 December 2016.
- Whinam J, Chilcott NM.** 1999. Impact of trampling on alpine environments in central Tasmania. *Journal of Environmental Management* 57:205–220. <http://dx.doi.org/10.1006/jema.1999.0302>.
- Whinam J, Chilcott NM.** 2003. Impact after four years of experimental trampling on alpine/sub-alpine environments in western Tasmania. *Journal of Environmental Management* 67:339–351. [http://dx.doi.org/10.1016/S0301-4797\(02\)00218-9](http://dx.doi.org/10.1016/S0301-4797(02)00218-9).
- Wiesmair M, Feilhauer H, Magiera A, Otte A, Waldhardt R.** 2016. Estimating vegetation cover from high-resolution satellite data to assess grassland degradation in the Georgian Caucasus. *Mountain Research and Development* 36(1):56–65.
- Xu L, Freitas SM, Yu FH, Dong M, Anten NP, Werger MJ.** 2013. Effects of trampling on morphological and mechanical traits of dryland shrub species do not depend on water availability. *PLoS One* 8:1–8. <http://dx.doi.org/10.1371/journal.pone.0053021>.
- Zagajewski B, Folbrier A, Kozłowska A, Sobczak M, Wrzesień M.** 2005. Zintegrowane pomiary roślinności wysokogórskiej. *Teledetekcja Środowiska* 36:61–68.
- Zagajewski B, Sobczak M, Wrzesień M, Kozłowska A.** 2006. Badania górskich zbiorowisk roślinnych z użyciem naziemnych technik hiperspektralnych. In: Mirek Z, Godzik B, editors. *Tatrzański Park Narodowy na tle innych górskich terenów chronionych. Tom II. Nauki biologiczne*. TatraNational Park, PTPNoZ - Oddział Krakowski, Zakopane, pp 125–136.
- Zarco-Tejada PJ, González-Dugo V, Berni JAJ.** 2012. Fluorescence, temperature and narrow-band indices acquired from a UAV platform for water stress detection using a micro-hyperspectral imager and a thermal camera. *Remote Sensing of Environment* 117:322–337. <http://dx.doi.org/10.1016/j.rse.2011.10.007>.
- Zha Y, Gao J, Ni S, Liu Y, Jiang J, Wei Y.** 2003. A spectral reflectance-based approach to quantification of grassland cover from Landsat TM imagery. *Remote Sensing of Environment* 87:371–375.
- Zwijacz-Kozica M.** 2010. Zróżnicowanie kosodrzewiny w świetle badań teledetekcyjnych. *Teledetekcja środowiska* 44, Warszawa.
- Zwijacz-Kozica M, Zwijacz-Kozica T, Zagajewski B.** 2010. Ocena wpływu turystyki i narciarstwa na stan kosodrzewiny w rejonie Hali Gąsienicowej na podstawie zdjęć hiperspektralnych. In: Kotarba A, editor. *Przyroda Tatrzańskiego Parku Narodowego a Człowiek. Nauka a zarządzanie obszarem Tatr i ich otoczeniem*. Tatra National Park. Polskie Towarzystwo Przyjaciół Nauk o Ziemi. Oddział Krakowski, Zakopane, T.II, pp 81–86.

## Supplemental material

**Table S1** Statistical significance of vegetation indices for the analyzed species (sample size for each species:  $n = 30$ ).

**Table S2** Trampling tolerance of the analyzed species determined on the basis of statistical significance of vegetation indices (sample size for each species:  $n = 30$ ).

All found at DOI: <http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00050.S1> (134KB PDF).