A New Method for Bryophyte Canopy Analysis Based on 3D Surface Reconstruction

Michal Krumnikl, Eduard Sojka, Jan Gaura
VŠB - Technical University of Ostrava
Department of Computer Science
17. listopadu 15/2172, 708 33 Ostrava, Czech Republic
Michal.Krumnikl@vsb.cz, Eduard.Sojka@vsb.cz, Jan.Gaura@vsb.cz

Oldřich Motyka
University of Ostrava
Department of Biology and Ecology
Chittusiho 10, 710 00 Ostrava, Czech Republic
oldrich.motyka@email.cz

Abstract

Recent studies concerning bryophyte canopy structure applied various modern, computer analysis methods for determining moss layer characteristics drawing on the outcomes of a previous research on surface of soil. Surface roughness index (L_r) was hereby used as a monitor of quality (and condition) of bryophyte canopy.

We explored stereo photogrammetry, a non-contact passive method of collecting distance information about surfaces, as a method to acquire 3D model of bryophyte layer and thus L_r and compared it with methods already performed by other authors - contact probe, LED scanning and 3D laser scanning.

In contrast to active methods, this method relies on detecting reflected ambient light, therefore, it does not emit any kind of radiation, which can lead to interference with moss photosynthetic pigments, nor does it affect the structure of its layer. This makes it much more suitable for usage in natural environment.

Other advantage of this method is eminently shorter measuring time and mobility, 3D surface can be reconstructed immediately after acquiring the images from two portable cameras, also, compared to scanners, this method is not the drawback of being dependent on heavy mechanical device moving the scanned object below the sensor.

The density of acquired surface points is dependent on the hit rate of stereo matching algorithms – algorithms searching for the corresponding points in both images. So far, no fully satisfactory algorithm has been found. These algorithms are generally not optimized for micro images and have to be altered to increase their efficiency. sed on contact probe, LED and laser scanning techniques.

The measuring resolution matches the resolution of LED scanner, since both are using similar cameras. Final resolution is not so high as laser scanner, but in addition to other its advantages, it makes stereo photogrammetry useful tool for our purposes.

1. Bryophyte Structure

Bryophytes are plants of a rather simple structure, they lack of roots and conductive tissues of any kind or even structural molecules that would allow establishment of their elements such as lignin[6]. The water which is generally needed for metabolic processes including photosynthesis is in the case of bryophytes also necessary for reproductive purposes, for their spermatozoids, particles of sexual reproduction, are unable to survive under dry conditions[5]. This makes them, unlike tracheophytes (vascular plants), poikilohydric – strongly dependent on the water conditions of their vicinity[21] – which led to several ecological adaptations of them. One of the most important adaptations is forming of a canopy – more or less compact layer of moss plants, frequently of a same clonal origin, which enables the plants to share and store water on higher, community level.

Canopy characteristics differ from species to species, this led certain authors to divide them to number of distinguished categories, so called growth forms[13][18][2]. Particular growth forms shows correlation with habitat[12], in case of epiphytic bryophytes they even show species host specificity to the bark substrate they live on[14] and also, there is a connection between growth form and life history of individual moss canopy[8]. The community level adaptations seems to affect the water balance of the moss layer the most respectively and eminently participates in the water loss control in *Polytrichum*[27], surface structure of the moss layer has great effect on properties of thickness and conductance of boundary layer – region of still air near the moss surface, the major impediment to water loss[24][22]. Canopy surface characteristics have been found to be related to carbon content of a cushion-forming epiphytic moss[31].

Bryophyte species in general have characteristics of applicable biomonitors and since 1968, when Rühling and Tyler first used mosses as bioindicators of lead in atmosphere, they have been used as both passive and active biomonitors of the environment commonly[26][3][10]. However, suitability of growth form of moss and thus structural properties of the canopy is also known[9], growth form has been also found to be able to reconstruct post climate change[11] and recent research implies that growth form can be even more suitable for bioindicative purposes than species itself[19].

As we can see from these examples, moss canopy properties are both in relation with environment of moss layer (thus important as bioindicator) and with biophysical characteristics of the canopy (thus important as microenvironment). Therefore, further knowledge and establishment of study methods of bryophyte canopy properties is necessarily needed to determine correlations between canopy structure and both macro- and micro-environmental factors.

Recent infrequent studies concerning bryophyte canopy structure applied various modern, computer analysis methods to determine moss layer characteristics drawing on the outcomes of a research on surface of soil[7]. Surface roughness index (L_r) has been hereby used as a monitor of quality and condition of moss layer, other indices, i.e. the scale of roughness elements (Sr) and the fractal dimension (D) of the canopy profile have been used and found to be important as well[22]. As stated in Rice[23], contact probe, LED scanner and 3D laser scanner were used and compared in light of efficiency and serviceability in 27 canopies of different growth forms. However, none of the methods already assessed have not been found to be convenient for field research, especially due to the immobility of used equipment and therefore needed dislocation of the surveyed moss material into the laboratory. This has great disadvantage in destroying the original canopy not only due to the transfer and excision from its environment, but also due to different much dryer conditions affecting moss surface in laboratory.

Method used in this study stereo photogrammetry has not been assessed for bryophyte canopy study yet, though it has been used for the purpose of evaluation of surface of soil[25]. Great advantage of this method, in comparison to other methods recently used, lies in the ability of collecting moss surface data in real time and in natural conditions.

2. Former Methods

The most significant research in the field canopy structure scanning has been conducted by Steven K. Rice, Department of Biological Sciences, Union College, Schenectady, NY 12308, USA. Rice analysed canopy structure among 35 canopies from 11 moss and liverwort taxa by using contact probe. These data were analysed using a geostatistical technique based on the semivariance statistic to characterize variation in three structural parameters: roughness height (i.e. average depth of roughness elements, L_r), average separation distance of roughness elements, and nescale roughness (i.e. surface irregularities within leaves and branches)[24][23].

Contact probe provided depth measures to the nearest 0.1 mm. All measurements represented the depth of first contact with canopy structure. Depths were sampled on the area of 5×5 cm^2 using the 0.5 cm grid and two transects through the center of the sampling area using 0.1 cm grid. Structural analysis were based on 223 depth measurements.

In his later research, Rice enhanced the scanning technique by using the LED and laser scanning techniques[23]. Original method using the surface contact probes is time-consuming, requires the contact with canopy and is incapable of measuring large surfaces.

Laser scanners were already used to measure soil surface roughness. Rice suited this technique to measure bryophytes, but also draw attention to the fact that bryophyte structure may be compromised by the inherent organization of bryophyte canopies[23]. The higher levels of canopy structure may obstruct the camera view and create gaps in acquired data grid. Rice performed the laser scanning with a Replica 3D scanner with Reversa 25 optics. This system had an accuracy of 30 μm (measured as the standard deviation of depth measurements on a smooth sphere). The scanner was optimized for white surfaces, thus canopy structure had to be coated with white spray paint. For each sample, a 5×5 cm^2 area was scanned at a grid scale of 0.4 mm. This sampling procedure provided a potential maximum of 15 876 sample points. During the experiments he obtained data for between 13% and 82% of possible sample points. All canopies scanned using the laser approach reached a maximum semivariance value within 2.5 cm[23].

Rice has also developed a portable scanner using LED, working similar to commercial laser scanner. The LED scanner was using LS1900 series laser diode to emit a 1 mm wide light stripe. The intersection between the light stripe and canopy was detected with a Pixera digital camera, 1.2 megapixels with macro lens F/2.1, f = 5 mm. This instrument had an accuracy of 0.5 mm. Samples were mounted on mechanical stage allowing displacement in the X-direction. Sampling area was 6.5×5 cm^2 with 2 mm grid in the X-directions, providing maximum of 10 920 potential sampling points. This scanning method provided data for between 21% and 88% of possible sample points. All scanned canopies reached the same maximum semivariance as with the laser approach[23].

3. Bryophyte Canopy Analysis

The former methods are suitable and efficient for measuring structural parameters in laboratory, but generally are impracticable in the field. Despite the LED scanner is presented as a portable device, it has high demands for proper settings and conditions that has to be maintained.

The method described in this paper presents a new approach using the pair of cameras as the scanning device. Computer analysis involving 3D reconstruction and soil roughness compensation is used to calculate the canopy surface roughness. The main goal was to create a device that can be used in the field, needs a minimum time for settings and is able to operate in the variety of environments.

Our device is composed of hardware parts – optical system consisting of two cameras and software, analysing acquired images. The images are acquired from two IDS Imaging cameras (2240-M-GL, monochromatic, 1280x1024 pixels, 1/2" CCD with lenses PENTAX, f=12 mm, F1.4) firmly mounted in a distance of 32.5 mm between them (Figure 1). Images has been taken in normal light, no auxiliary lamp was used.

The optical system has to be calibrated after assembly. Calibration data obtained from the software calibration procedure are valid as long as there is no change in construction or lens settings. The process of surface reconstruction and roughness calculation is described in the following sections.

4. Bryophyte Canopy 3D Reconstruction

A method and a software system have been developed to carry out the 3D reconstruction of bryophyte canopy surface. The following main steps leading to reconstruction of a canopy are performed by particular parts of the system: (i) calibration of the optical system (i.e., the pair of cameras), (ii) 3D reconstruction of the bryophyte canopy surface itself. In the sequel, the mentioned steps will be described in more details.

In the calibration step, the parameters of the optical system are determined, which includes determining the intrinsic parameters of both the cameras (focal length, position of the principal point, coefficients of nonlinear distortion of the lenses) and the extrinsic parameters of the camera pair (the vector of translations and the vector of rotation angles between the cameras). For calibrating, the chessboard calibration pattern is used. The calibration is carried out in the following four steps: (1) creating and managing the set of calibration images (pairs of the images of calibration patterns captured by the cameras), (2) processing the images of calibration patterns (finding the chessboard calibration pattern and the particular calibration points in it), (3) preliminary estimation of the intrinsic and the extrinsic parameters of the cameras, (4) final iterative solution of all the calibration parameters. Typically, the calibration is done only from time to time and not necessarily at the place of measurement.

Figure 1. The pair of cameras mounted on the tripod

For solving the tasks that are included in Step 2, we have developed our own methods that work automatically. For the initial estimation of the parameters (Step 3), the method proposed by Zhang[29, 30] was used (similar methods may now be regarded as classical; they are also mentioned, e.g., by Heikilla and Silven[16], Heikilla[15], Bouguet[4] and others). The final solution of calibration was done by the minimisation approach. The sum of the squares of the distances between the theoretical and the real projections of the calibration points was minimised by the Levenberg-Marquardt method.

If the optical system has been calibrated, the surface of the bryophyte canopy may be reconstructed, which is done in the following four steps: (i) capturing a pair of images of bryophyte, (ii) correction of geometrical distortion in the images, (iii) rectification of the images, (iv) stereomatching, (v) reconstruction of the bryophyte surface.

Distortion correction removes the geometrical distortion of the camera lenses. The polynomial distortion model with the polynomial of the sixth degree is used. The distortion coefficients are determined during the calibration.

Rectification of the images is a computational step in which both the images that are used for reconstruction are transformed to the images that would be obtained in the case that the optical axes of both cameras were parallel. The rectification step makes it easier to solve the subsequent step of finding the stereo correspondence, which is generally difficult. The rectification step is needed since it is impossible to guarantee that optical axes are parallel in reality. We have developed a rectification algorithm that takes the original projection matrices of the cameras determined during calibration and computes two new projection matrices of fictitious cameras whose optical axes are parallel and the projection planes are coplanar. After the rectification, the corresponding points in both images have the same y-coordinate.

The dense stereo matching problem consists of finding a unique mapping between the points belonging to two images of the same scene. We say that two points from different images correspond one to another if they depict a unique point of a three-dimensional scene. As a result of finding the correspondence, so called disparity map is obtained. For each image point in one image, the disparity map contains the difference of the x-coordinates of that point and the corresponding point in the second image. The situation for finding the correspondence automatically is quite difficult in the given context since the structure of bryophyte canopy is quite irregular and, in a sense, similar to noise. We have tested several known algorithms for this purpose. The results of none of them, however, are fully satisfactory for the purpose of reconstructing the bryophyte canopy. Finally, we have decided to use the algorithm that was proposed by Ogale and Aloimonos[20] that gave the best results in our tests.

Once the disparity map is found, the bryophyte canopy surface visible in the images may be found quite easily. In Figure 2, the result of bryophyte canopy 3D surface reconstruction is shown.

5. Surface Roughness

Surface roughness is a measurement of the small-scale variations in the height of a physical surface of bryophyte canopies.

For statistical evaluation of every selected bryophyte, we fitted all measured z-component values that we obtained from the 3D reconstruction (4) with a plane[17]. This plane then represents the mean value of measured z-component. For this step, we have already a full set of x-, y-, and z-components from the previous reconstruction process. The plane is defined by $Ax + By + Cz = D$, where A, B, and C denote components of the normal of the plane ($\mathbf{n} = (A, B, C)$).

The signed distance between a point $p_i = (x_i, y_i, z_i)$ and the plane is $d_i = Ax_i + By_i + Cz_i - D$. In this case, we are assuming normalized plane (i.e. $A^2 + B^2 + C^2 = 1$).

In a given set of points $p_i, i = (1, \ldots, n)$, we need to find a plane such that the distances between p_i and the plane is minimized. The d_i may be of positive or negative value, an appropriate minimization of d_i is the least squares method, in which we are finding A, B, C, and D as a minimum of

$$f(A, B, C, D) = \sum_{i=1}^{n} d_i^2. \tag{1}$$

Thereafter we want to solve the following system of linear equations

$$\frac{\partial f}{\partial A} = 0, \quad \frac{\partial f}{\partial B} = 0, \quad \frac{\partial f}{\partial C} = 0, \quad \frac{\partial f}{\partial D} = 0. \tag{2}$$

From the equation $\frac{\partial f}{\partial D} = 0$, we obtain $D = Ax_c + By_c + Cz_c$ where

$$x_c = \frac{\sum_{i=1}^{n} x_i}{n}, \quad y_c = \frac{\sum_{i=1}^{n} y_i}{n}, \quad z_c = \frac{\sum_{i=1}^{n} z_i}{n}. \tag{3}$$

The above equations show that the best fitting plane passes through the center of the mass denoted by x_c, y_c, z_c. By substracting the center of the mass from the each point and substituting the difference into Equations (2), we obtain a system of equations (note that the least squares plane will pass through the origin)

$$WP = 0, \tag{4}$$

where $P = [A, B, C]^T$. The system (4) has a trivial solution $A = B = C = 0$. To obtain a non-trivial solution, we may require $A^2 + B^2 + C^2 = 1$. With such a constraint, it can be shown that the solution becomes an eigenvalue problem

$$WE = VE, \tag{5}$$

where V are the eigenvalues and E the eigenvectors. Solution of the Equation (5) produces three eigenvalues and a 3×3 matrix of eigenvectors. The three eigenvectors are orthogonal and define a thee sets of A, B, and C. They represent the best, intermediate, and the wost planes. By choosing the smallest eigenvalue and associated eigenvector, we have the set of A, B, and C that represent the best fitting plane.

We have implemented two different solvers of plane fitting problem. One that is written in the C language and is integrated into our measurement software, and the testing one that is implemented in the GNU Octave language.

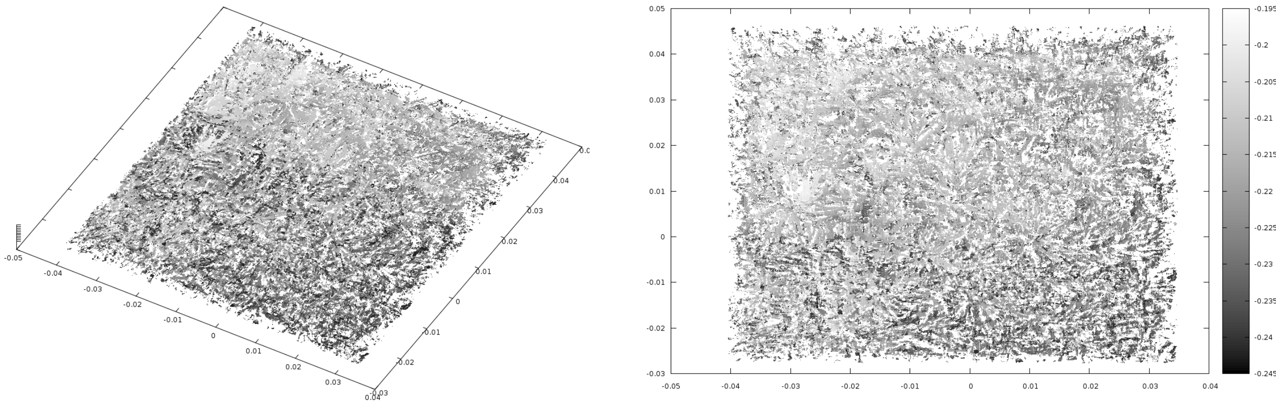

Figure 2. Results of 3D reconstruction of canopy surface (*Polytrichum formosum*)

In order to calculate the surface specific parameters, we have to minimize the impact of subsoil segmentation. We have performed a linear regression using the expression above to interpolate the subsoil surface. Thus we have obtained the plane that represents the average canopy level. The distances from the reconstructed z-coordinates and the fitting plane were evaluated statistically.

Canopy structure can be characterized by the surface characteristics. The most common measure of statistical dispersion is the standard deviation, measuring how widely z-values are spread in the sample. Standard deviation[28] is computed as

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(z_i - \mu)^2}{N}}. \qquad (6)$$

Bryophyte canopy structure is also described by L_r parameter defined by Rice as the square root of twice the maximum semivariance[22]. Semivariance is described by

$$\widehat{\gamma}(h) = \frac{1}{2n(h)}\sum_{i=1}^{n(h)}(z(x_i + h) - z(x_i))^2, \qquad (7)$$

where z is a value at a particular location, h is the distance between ordered data, and $n(h)$ is the number of paired data at a distance of h[1].

6. Results and Discussion

The 3D reconstruction performed on the system of our own construction had an average accuracy of 0.1 mm, measured on testing images with scale and objects of known dimensions.

To evaluate the applicability of canopy surface measurements, based on 3D reconstruction, we have analysed ten image samples of two bryophytes representing the quite different structure – *Polytrichum formosum* and *Atrichum undulatum*. We also tried to observe mat-forming moss *Hypnum cupressiforme* but our specimen did not survive under laboratory conditions, this led to the destruction of its canopy.

Canopy depth were obtained from the area of about 5×5 cm (observer interquartile range was $Q(z)_{10} = -0.0177, Q(z)_{90} = 0.0142$). The scanned area provided more than 600000 depth points that were used to calculate surface parameters.

Previously mentioned accuracy is sufficient for characterising the canopy structure considering the average bryophyte depth of about 20 mm. By comparing the standard deviation of *Polytrichum formosum* surface ($\sigma = 0.0109$, 95% confidence interval 0.0104–0.0115, $n = 5$) and *Atrichum undulatum* ($\sigma = 0.0125$, 95% confidence interval 0.0121–0.0129, $n = 5$), we have verified the ability of bryophyte canopy differentiation based on the surface characteristics.

The basic limit of our approach is the success rate of dense stereo match algorithm. Finding the corresponding points automatically is quite difficult, especially in cases where canopy structure is vague and indifferent. Improper corresponding points lead to abnormalities and inaccuracy of reconstructed surface, likewise derived statistical values.

Since this is a preliminary evaluation of the bryophyte canopy analysis based on 3D surface reconstruction, further examination has to be made involving the extended range of bryophyte species and environmental conditions. Additional surface characteristics will be exploited involving the comparison of surface roughness published by Rice[23].

While the techniques used in the past were successful in laboratory environment, the analyser based on 3D image reconstruction may become the real in-field measurement apparatus. It simplifies the research involving surface roughness and accelerates the calculation. Oncoming research will involve utilization of this method for real-time observations.

References

[1] M. Bachmaier and M. Backes. Variogram or semivariogram - explaining the variances in a variogram. *Precision Agriculture*, 2008.

[2] J. W. Bates. Is "life-form" a useful concept in bryophyte ecology? *Oikos*, (82):223–237, 1998.

[3] D. Bielec. Mszaki i porosty jako biowskaźniki zanieczyszczeń powietrza. *Materialy z IV Konferencji Zapobieganie zanieczyszczeniu środowiska Politechnika Lodzka Filia w Bielsku-Bialej*, (41):197–214, 1997.

[4] J.-Y. Bouguet. Camera calibration toolbox for matlab. *http://www.vision.caltech.edu/bouguetj/calib_doc/-index.html*, 2005.

[5] H. J. Brodie. The splash-cup dispersal mechanism in plants. *Canadian Journal of Botany*, (29):224–230, 1951.

[6] H. Crum. *Structural Diversity of Bryophytes*. University of Michigan Herbarium, Ann Arbor, 2001.

[7] F. Darboux and C. Huang. An simultaneous-profile laser scanner to measure soil surface microtopography. *Soil Science Society of America Journal*, (67):92–99, 2003.

[8] H. J. During. Life strategies of bryophytes: a preliminary review. *Lindbergia*, (5):2–18, 1979.

[9] H. J. During. *Ecological classifications of bryophytes and lichens*. Bryophytes and Lichens in a Changing Environment, Oxford Science Publications, 1992.

[10] J. Falla, P. Laval-Gilly, M. Henryon, D. Morlot, and J.-F. Ferard. Biological air quality monitoring: a review. *Environmental Monitoring and Assessment*, (64):627–644, 2000.

[11] L. D. Gignac. Bryophytes as indicators of climate change. *The Bryologist*, (104):410–420, 2001.

[12] C. H. Gimingham and E. M. Birse. Ecological studies on growth forms in bryophytes. i. correlations between growth form and habitat. *Journal of Ecology*, (45):533–545, 1957.

[13] C. H. Gimingham and E. T. Robertson. Preliminary investigations on the structure of bryophytic communities. *Transactions of the British Bryological Society*, (1):330–344, 1950.

[14] J. M. Gonzáles-Mancebo, A. Losada-Lima, and S. McAllister. Host specificity of epiphytic bryophyte communities of a Laurel Forest on Tenerife (Canary Islands, Spain). *The Bryologist*, (106):383–394, 2003.

[15] J. Heikilla. Geometric camera calibration using circular control points. *IEEE Transactions on Pattern Analysis and Machine Intelligence 22*, (10):1066–1077, 2000.

[16] J. Heikilla and O. Silven. A four-step camera calibration procedure with implicit image correction. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR97)*, pages 1106–1112, 1997.

[17] S. A. Islam. Math notes. *www.bmm.icnet.uk/people/suhail/-plane.html*, (15), July 1999.

[18] K. Mägdefrau. Life-forms of bryophytes. *Bryophyte ecology*, 1982.

[19] N. Nöske. *Effekte anthropogener Störung auf die Diversität kryptogamischer Epiphyten (Flechten, Moose) in einem Bergregenwald in Südecuador*. Ph.D. dissertation, Georg-August-Universität zu Göttingen, 2004.

[20] A. Ogale and Y. Aloimonos. Shape and the stereo correspondence problem. *International Journal of Computer Vision*, 65(3):147–162, December 2005.

[21] M. C. F. Proctor and Z. Tuba. Poikilohydry and homoiohydry: antithesis or spectrum of possibilites? *New Phytologist*, (156):327–349, 2002.

[22] S. K. Rice, D. Collins, and A. M. Anderson. Functional significance of variation in bryophyte canopy structure. *American Journal of Botany*, (88):1568–1576, 2001.

[23] S. K. Rice, C. Gutman, and N. Krouglicof. Laser scanning reveals bryophyte canopy structure. *New Phytologist*, 166(2):695–704, May 2005.

[24] S. K. Rice and N. Schneider. Cushion size, surface roughness, and the control of water balance and carbon flux in the cushion moss *leucobryum glaucum* (leucobryaceae). *American Journal of Botany*, (91):1164–1172, 2004.

[25] D. Rieke-Zapp, H. Wegmann, F. Santel, and M. Nearing. Digital photogrammetry for measuring soil surface roughness. *ASPRS Annual Convention, St. Louis*, 2001.

[26] A. Rühling and G. Tyler. An ecological approach to the lead problem. *Bod. Notiser*, 1968.

[27] V. Sarafis. A biological account of polytrichum commune. *New Zealand Journal of Botany*, (9):711–724, 1971.

[28] E. W. Weisstein. Standard deviation, a wolfram web resource. *http://mathworld.wolfram.com*.

[29] Z. Zhang. Flexible camera calibration by viewing a plane from unknown orientations. In *International Conference on Computer Vision (ICCV'99), Corfu, Greece*, pages 666–673, 1999.

[30] Z. Zhang. A flexible new technique for camera calibration. *IEEE Transactions on Pattern Analysis and Machine Intelligence 22*, (11):1330–1334, 2000.

[31] G. Zotz, A. Schweikert, W. Jetz, and H. Westermann. Water relation and carbon content are closely relative to the cushion size in the moss *grimmia pulvinata*. *New Phytologist*, (148):59–67, 2000.