Univerzita Karlova, Přírodovědecká fakulta
Ústav pro životní prostředí
Charles University, Faculty of Science
Institute for Environmental Studies

Doktorský studijní program: Environmentální vědy

Doctoral study programme: Environmental Science

Autoreferát disertační práce
Summary of the Doctoral thesis

Využití dat dálkového průzkumu Země pro sledování dlouhodobé dynamiky vegetace na krajinném měřítku

Use of remote sensing data for monitoring of long-term vegetation dynamics on the landscape scale

Mgr. Josef Brůna

Školitel/Supervisor: doc. Ing. Jan Wild Ph.D.

Praha, 14.6.2018

Abstract in Czech

Tato disertační práce se věnuje především využití dat dálkového průzkumu pro sledování a studium změn vegetace. Díky archivním materiálům můžeme dnes provádět rozsáhlé studie na úrovni krajiny i celého světa bez potřeby rozsáhlých nebo archivních terénních dat. Od středověku se můžeme opřít o různé typy map, pro studium vegetace především lesnických. Od 30. let 20. století jsou v Evropě dostupné letecké snímky a od 70. let pak snímky satelitní, jejichž dostupnost a kvalita v době mého studia rapidně vzrostla. Nejnovějším příspěvkem v této oblasti jsou bezpilotní prostředky a metody jejich zpracování, které umožňují detailní mapování rozsáhlých ploch s nízkými náklady. Kromě výzkumných ekologických otázek, mají zde prezentované práce i environmentální rozměr a různou měrou přispívají k řešení aktuální problémů české ochrany životního prostředí od ochrany přírody v národních parcích a chráněných oblastech až po monitoring rostlinných invazí.

Archivní lesnické mapy jsem využil k rekonstrukci a analýze rozsáhlých disturbancí (polomů a následné gradace lýkožrouta smrkového) v lesích Šumavy a Bavorského lesa v letech 1868-1870. Analyzována byla nejen druhová skladba, ale i faktory prostředí odvozené z digitálního modelu terénu. Stejnému tématu se pak věnovala analýza predispozic lesa k napadení lýkožroutem smrkovým využívající archivu dat satelitů Landsat. Archivní a současné letecké snímky jsem využil pro modelování zarůstání opuštěné krajiny v Doupovských horách, kde jsem opět využíval faktory prostředí odvozené z digitálního modelu terénu. Analýza vývoje od roku 1952 ukazuje změny prostředí, které by během terénních prací nebylo možné postihnout. I zde je cenným zdrojem informací mapa původního využití půdy, která nahrazuje terénní průzkum v době zániku sídel.

Díky rozvoji bezpilotních prostředků je dnes možné monitorovat výskyt jednotlivých druhů rostlin, čemuž jsme se věnovali v článcích věnujících se detekci invazních rostlin. Zde jsou důležitým zdrojem dat především terénní data o výskytu jednotlivých druhů pro kalibraci a validaci. Současné pokroky strojového zpracování velkého množství obrazových dat slibují značný rozvoj tohoto oboru v nadcházejících desetiletích. I nadále však budou archivní data důležitá pro pochopení předchozího vývoje.

Abstract in English

This thesis deals with the use of remote sensing data for studying and monitoring vegetation changes. Thanks to archival materials, we can now make extensive studies at the landscape and global level without the need for large-scale old field data. From the Middle Ages, we can rely on different types of maps, for vegetation studies, these are mainly forestry maps. Since the 1930's, aerial photographs have been available in Europe, and satellite imagery was available since the 1970's. Availability and quality of satellite imagery had increased rapidly during my study. The most recent data source are unmanned aerial systems and methods of processing their data, which allow inexpensive detailed mapping of large areas. The presented publications do not only solve ecological research questions, but also contribute to solving current environmental problems in the Czech Republic, from nature conservation in National Parks and protected areas to monitoring of plant invasions.

I have used archival forest maps for the reconstruction and analysis of large disturbances (windthrow and subsequent gradations of bark beetle) in forests of Šumava and the Bavarian Forest in 1868-1870. Species composition, as well as environmental factors derived from digital elevation model, were analyzed. The same topic was also studied in the current analysis of forest predisposition to bark beetle attack using the Landsat satellites data archive. I have used archival and contemporary aerial imagery for modeling of secondary succession of the abandoned landscape in the Doupov Mountains. Once again, environmental factors derived from the digital terrain model were used for analysis of development since 1952. The results show long-term changes in the environment that could not have been covered by fieldwork. Old cadastral map from the time of abandonment was also used here as a valuable source of data to understand the predispositions for change.

Thanks to the development of unmanned aerial systems it is now possible to monitor the occurrence of individual plant species, as we have done in articles dealing with the detection of invasive plants. This type of research relies on field data on the occurrence of individual species for calibration and validation. The current advances in machine processing of large amounts of image data promise considerable development in this field over the coming decades. However, archival data will continue to be important for understanding previous development.

Summary of the Doctoral thesis

1. Introduction

The occurrence of trees and plants is determined by environmental conditions, disturbance regime, competition between coexisting species, interactions with herbivores and other influences. However, the significance of some factors is evident on a larger spatial scale, particularly the importance of species spreading, historical species distribution and large-scale disturbances. Processes on a landscape scale can significantly modify local events or their outcomes. Knowledge of the landscape context is therefore necessary to understand the development of vegetation cover over longer periods of time. One possible approach is the mathematical modeling of natural processes based on knowledge of population-biological characteristics of species, but the required information is not always available. Permanent study plots are often used to assess long-term vegetation changes. They provide valuable data, but maintenance costs are high. Remote sensing and geographic information systems (GIS) can deliver data for similar studies even in places where long-term data collection has not taken place. In my thesis, I had used several available types of remote sensing data to answer various ecological questions relevant to current nature protection problems in the Czech Republic.

2. Aims of the thesis

The main aims of my thesis are methodological and ecological. Available processing methods are rarely ideal for the ecological question in mind. Therefore, for every study that uses remote sensing, there are modifications and new processes needed to produce the best results.

- My first methodological aim was to use object-oriented classification of aerial images to derive relevant ecological data for monitoring vegetation changes semi-automatically.
    - I have focused on this aim in **Papers II**, **IV** and **V (numbers can be found in the Selected publication list)**.
- My second methodological aim was to use archival data to enable long-term studies even without old field data.
    - I have focused on this aim in **Papers I** and **III**.
- My third methodological aim was to prepare a method for practical application of unmanned aerial vehicle (UAV) for monitoring of invasive plant species in nature conservation.
    - I have focused on this aim in **Papers IV** and **V**.
- The ecological questions of my thesis are connected to the spatial dimension of several ecological processes.
    a. Are large-scale disturbances part of a historical range of variability of central European mountain spruce forests? What are the drivers behind spatial differences of impacts of large-scale disturbances?

- I have focused on this aim in **Papers I** and **III**.

b. What are the main drivers behind secondary succession speed and course in an abandoned landscape?
    - I have focused on this aim in **Paper II**.

3. Materials and methods

The papers presented in this thesis cover a range of topics but share similar methods and data and finding the right workflow and settings, to deliver the best data for each ecological question, was a crucial part of all the studies. Repeated black and white aerial survey photography is available in many countries of Europe (Cousins and Ihse, 1998; Lofman and Kouki, 2001) and USA (Turner and Ruscher, 1988) since 1930's. We have used old aerial imagery from every decade between 1952 and 2015 in **Paper II** to model landscape scale secondary succession of an abandoned agricultural landscape in Doupovské hory. Since 1972, the world is continuously monitored by commercial satellites, and the Landsat missions gathered an unprecedented archive of imagery that still grows. For a long time, the price of the images limited research and applications but in 2008, the US Geological Survey (USGS) made the data from the Landsat archive freely available for everyone (USGS, 2008; Woodcock et al., 2008). This revolutionized how Landsat data are used and accelerated the use of multitemporal data for change detection (Wulder et al., 2012). Our study (Hais et al., 2016, **Paper III**) also benefited from this, although we have used only 16 scenes to derive spectral trajectories. And even though satellite imagery cannot provide a direct measure of forest vitality these spectral trajectories help to predict forest stands vulnerable to bark beetle attack.

Spatial data also face problems with spatial autocorrelation. Many statistical tests require independent samples, and therefore various methods are used to generate valid samples from remote sensing. We have used regular grid sampling and tested spatial autocorrelation using Moran I (Sokal and Oden, 1978) in **Papers I, II** and **III** to identify the best sampling distance. Studies usually rely on field data for calibration and validation which enables the researchers to extrapolate the local knowledge to larger areas (Bird et al., 2000). To understand the context better, scientists use older imagery and archival data including archival maps like land economic inventories (White and Mladenoff, 1994), topographic maps (Fuchs et al., 2015) or old military survey maps (Skaloš et al., 2011). Computer processing in GIS and statistical analysis help to derive even more from these maps as we did in **Paper I**, where the archival maps and forestry books of the Czech part of Šumava were already processed manually by (Jelínek, 2005, 1988) but environmental factors behind the variability of disturbance intensity and the effect on stand age were not tested before us.

The real power of remote sensing data is in combination with spatial variables derived from field data or other sources. The most versatile data source is a digital elevation model (DEM) that can be used to derive indexes that serve as a proxy for data, which are not easy to collect in the field. We had used several different indexes in **Papers I, II** and **III** and in Čuda et al. (2017) to test drivers of large-scale processes derived from a LiDAR DEM with 5 m resolution and 1 m vertical error (DMR 4G from ČÚZK, www.cuzk.cz). The most useful indexes for vegetation studies are heat load index (HLI) which describes the variation in potential solar radiation (McCune and Keon, 2002), Insolation (Böhner and Antonić 2009) which adds terrain features into the calculation and sums it throughout the year with respect to position of sun, topographic Wetness Index (TWI; Beven and Kirkby, 1979) used as a proxy for available water, Topographic Position Index (TPI; Guisan et al., 1999) defining local terrain features against their neighbourhood as well as Terrain ruggedness index (Riley et al., 1999) as a measure of topographic heterogeneity. For forest-related studies, we also use morphometric protection index, equivalent to the positive openness described in Yokoyama et al. (2002). For cross-border and global studies, these can be derived from ASTER Global Digital Elevation Model V002 (METI/NASA, 2011) as we have done in **Paper I**, or from SRTM, TANDEM-X or derived models. The choice of the model influences the results, and it is therefore crucial to select the best one for each particular study (Moudrý et al., 2018).

The newest trend in remote sensing is the use of unmanned aerial vehicles (UAVs) that combine the benefits of remote sensing with the flexibility of field data collection. They cannot compete with the spatial and temporal coverage of satellites, but they offer higher spatial and temporal resolution (Manfreda et al., 2018). We had used purposely built UAV for monitoring of invasive species in **Papers IV** and **V**. Combining imagery from several acquisitions across a vegetation season, we have used differences in phenology to distinguish several invasive species from similarly looking surrounding vegetation (white flowering *Heracleum mantegazzianum* and *Robinia psedoacacia* in May; dry *Reynoutria sp.* in November).

The initial part of remote sensing studies involves radiometric and geometric corrections. With satellite imagery, geometric corrections are mostly provided for all products, and it is possible to obtain radiometrically corrected data as well, or use established algorithms like MADCAL (Canty et al., 2004) as Martin Hais did in our **Paper III.** The same is true for recent aerial imagery, which is usually orthorectified by the producer, but older images need to be orthorectified by the user. Orthorectification and mosaicking of old aerial images was not an automatic task when I started, and the data for **Paper II** was mostly prepared using a lot of manual input to identify tie points and mosaic the scanned original aerial survey photographs. However, the process became easy with Structure from Motion method (SFM; Dandois and Ellis, 2010; Westoby et al., 2012) that can match hundreds of photographs from UAVs into a single image as we did when preparing data for **Papers IV** and **V**.

The next step after creating the orthomosaic is usually classification; this can be supervised or unsupervised based on the amount of input information. I have used only supervised classification in all the papers based on training samples from the field. Regardless of the level of supervision, there are two main approaches to the classification used in remote sensing. Pixel-based approach uses only spectral information of every single pixel to determine its class, whereas the object-based classification approach (Blaschke, 2010; Blaschke et al., 2014; Hay et al., 2003) merges neighboring pixels using segmentation techniques such as multiresolution segmentation (Baatz and Schäpe, 2000) into objects and classifies the whole resulting objects based not only on brightness, but also on spatial structure, heterogeneity and context information. This is especially useful, if the classification target is covered by several pixels and has distinct shape like flowering *Heracleum mantegazzianum* on UAV imagery in **Paper V**. It is also useful for quick classification of large structures like trees and shrubs among grasslands on aerial imagery like I did in **Paper II**, where a single bright pixel among a tree canopy was usually not a grassland. Even when target species or land cover class do not have distinct textural properties, this method can still help to classify the other classes more accurately. However, the simpler pixel-based classification is useful, especially in combination with machine learning algorithms. We also have successful results from pixel-based classification for detection of *Reynoutria sp.* on UAV data in **Paper V** using Support Vector Machines (Vapnik, 1995) and Random Forests (Breiman, 2001). Our results in **Paper III** also rely on pixel-based classification, because the 30 m pixels of Landsat images already cover several trees that can differ in vitality. The quality of classification results also relies on accurate field data that need to have high spatial precision and include independent samples for verification and validation purposes.

4. Results and discussion

I have analyzed archival forestry maps and materials of mountain spruce forests in Šumava and Bavarian Forest and identified impacts and factors underlying landscape-scale disturbances of mountain forests in 1868-1870 **(Paper I)**. These disturbances (windthrow and subsequent bark beetle attack) substantially altered the age and species structure of the forests. I have identified a positive effect of mean forest age on disturbance severity. Mean elevation in a 250 m circle, and effective air flow heights from constant wind direction (Boehner and Conrad, 2008) also had a positive effect on the severity of the disturbance. This means that spruce forests in higher elevations and exposed areas are more vulnerable. The most disturbed age group was forests older than 120 years. The forests that grew after the 1868-1870 disturbances reached the same age recently, and similar disturbances happened again in the area. We could now study details, which were not captured in the maps which combined windthrow and bark beetle damage. We have therefore focused on other pre-disturbance forest conditions that can be used to identify trees with a higher risk of bark beetle attack in **Paper III**. We have derived spectral trajectories of each component of Tasseled Cap linear transformation (Crist and Cicone, 1984; Kauth and Thomas, 1976) of a series of Landsat imagery and shown, that the Wetness index slope of the trajectory of images is an important variable to be considered for understanding the bark beetle infestation patterns. Its gradual decrease identifies the most vulnerable stands. At the beginning of the outbreak, edaphic conditions, heat load index and distance to wet areas influence the disturbance probability, later topographical wetness index (TWI; Beven and Kirkby, 1979), age and degree of naturalness of the forest play a role. If these trajectories and vulnerability maps were frequently provided to forest owners, much of the recent bark beetle outbreaks in the managed forests could have been prevented or at least the financial loss could have been lowered. The other possible solution based on our results from **Paper I** would be lowering the rotation age to avoid forests reaching the most vulnerable age.

Trajectories of images can also be prepared from aerial imagery. I have successfully adapted object-oriented classification method for monitoring of secondary succession in an abandoned landscape in **Paper II** using aerial imagery from every decade from 1952 to 2015. I have used median filtered images to help to segment the imagery and the brightness of the segmented objects and their texture based on Gray-Level Co-Occurrence Matrix (GLCM) features (Haralick et al., 1973) to classify woody vegetation and grasslands. The results and DEM derived variables helped me to identify factors behind the spatial pattern of succession on a landscape scale. The most important factor was the distance to nearest tree or shrub at the beginning of the modeled decade, which together with elevation and total insolation during vegetation season had a negative impact on succession. The density of trees and shrubs in the neighborhood, slope and TWI had a positive effect on succession towards a forest. Which means that most of the persisting grasslands are in dry, mostly flat areas in higher elevations, with high insolation and further away from forests and shrubs. These results confirm the general pattern of secondary succession in an abandoned landscape, but thanks to the series of images offer more in-depth insight into the process.

Some changes in the landscape are even faster, and these can be monitored using UAV imagery. In **Papers IV** and **V**, the results are methodological and cover detection of three invasive species using a novel approach based on custom-made UAV. I have designed an optimal workflow for field data collection using a combination of aerial imagery, UAV imagery and classified imagery in Collector for ArcGIS (**Paper IV**). This data is used for training, and validation purposes. We have identified the best time, type of data and classification method to distinguish each species. For *Robinia pseudoacacia* the best acquisition time is after flowering, and the classification relies on near-infrared data using a supervised pixel-based classification using Support Vector Machines (SVM; Vapnik, 1995) algorithms (**Paper IV**). I have identified, that the best time for classification of *Reynoutria sp.* in a typical riparian habitat is in November after its leaves turn red and the leaves of the surrounding trees had fallen already. If the area is without trees, the best time for detection is in the peak of vegetation season, when *Reynoutria sp.* is again highly distinguishable in the near infrared spectrum (**Paper V**). The best classification results in both acquisition times came from the supervised pixel-based approach and again an SVM classifier. These methodological results can also be used for deeper ecological studies, for example, if the high reflectance of invasive species in near infrared spectrum is a general property of an invasive plant. The spatial distribution of species can also be used for species distribution modeling and general prediction of invasion risk based on DEM derived variables.

5. Conclusions

During my studies, remote sensing options and techniques have developed rapidly. There are vast amounts of data for free or at a reasonable price and studies are no longer limited by imagery (**Paper III**). The hardware and software advances in image processing enabled automation of many tasks that were laborious when I started working with remote sensing data in 2007. This can be best seen in UAV image processing, where the whole process needs just a few inputs, and the resulting image has only a minor error in georeferencing, making use of repeated acquisitions even more straightforward and robust. Species recognition based on imagery is still a challenging task, but phenological difference during the season help to distinguish many problematic species. We had taken advantage of this in **Papers IV** and **V** for classification of *Robinia pseudoacacia*, *Heracleum mantegazzianum,* and *Reynoutria sp.* and also *Ailanthus altissima* in Müllerová et al. (2017). Field data are still crucial for validation and interpretation, but their collection became more comfortable as well with products like Collector for ArcGIS.

All the papers included in the thesis can be used for helping to solve current nature protection problems in the Czech Republic. Some in the form of a relevant argument based on significant field data, for scientific debate about the future management of National parks (**Papers I** and **III**) or about management interventions in smaller protected areas (**Paper II**), some as direct methods for nature protection practitioners (**Papers IV** and **V**). I consider the aims of my thesis to be fulfilled, I have successfully adapted object-oriented classification method for monitoring of secondary succession on an abandoned landscape (**Paper II**) and also helped to develop a complete applied methodology for the monitoring of selected invasive species that is best described in the certified methodology of Ministry of Environment (Müllerová et al., 2017) and in **Papers IV** and **V**. I have used archival maps for our study of large-scale disturbances of mountain spruce forests in NP Šumava and Bavarian Forest in the 19th century and identified impacts and factors underlying a landscape scale disturbance of a mountain forest. I have also shown that large scale disturbances are well within historical range of variability in the area **(Paper I)**. Using the time series of Landsat imagery to study recent bark beetle outbreaks around Březník, we have later identified indices that show the weakening of forest stands before bark beetle attack (**Paper III**). Old aerial imagery allowed me to study 70 years of succession even in areas with restricted entrance and sparse field records (**Paper II**). Using DEM derived variables, I have identified several important conditions that slow or alter the course of secondary succession on an abandoned landscape. I conclude, that remote sensing data are a valuable source for monitoring of long-term vegetation dynamics on the landscape scale and related ecological studies.

6. References

Baatz, M., Schäpe, A., 2000. Multiresolution segmentation— an optimization approach for high quality multiscale image segmentation, in: J., S. (Ed.), Angewandte Geographische Informationsverarbeitung XII. Beiträge Zum AGIT-Symposium Salzburg,. Herbert Wichman Verlag, Karlsruhe, pp. 12–23.

Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. *Hydrological Sciences Bulletin* 24, 43–69. doi: 10.1080/02626667909491834

Bird, a. C., Taylor, J.C., Brewer, T.R., 2000. Mapping National Park landscape from ground, air and space. *International Journal of Remote Sensing* 21, 2719–2736. doi: 10.1080/01431160050110250

Blaschke, T., 2010. Object based image analysis for remote sensing. *ISPRS Journal of Photogrammetry and Remote Sensing* 65, 2–16. doi: 10.1016/j.isprsjprs.2009.06.004

Blaschke, T., Hay, G.J., Kelly, M., Lang, S., Hofmann, P., Addink, E., Queiroz Feitosa, R., van der Meer, F., van der Werff, H., van Coillie, F., Tiede, D., 2014. Geographic Object-Based Image Analysis - Towards a new paradigm. *ISPRS Journal of Photogrammetry and Remote Sensing* 87, 180–191. doi: 10.1016/j.isprsjprs.2013.09.014

Boehner, J., Conrad, O., 2008. Effective Air Flow Heights.

Böhner, J., Antonić, O., 2009. Chapter 8 Land-Surface Parameters Specific to Topo-Climatology, in: Developments in Soil Science. Elsevier, pp. 195–226. doi: 10.1016/S0166-2481(08)00008-1

Breiman, L., 2001. Random forests. *Machine Learning* 45, 5–32. doi: 10.1023/A:1010933404324

Canty, M.J., Nielsen, A.A., Schmidt, M., 2004. Automatic radiometric normalization of multitemporal satellite imagery. *Remote Sensing of Environment* 91, 441–451. doi: 10.1016/j.rse.2003.10.024

Cousins, S.A.O., Ihse, M., 1998. A methodological study for biotope and landscape mapping based on CIR aerial photographs. *Landscape and Urban Planning* 41, 183–192. doi: 10.1016/S0169-2046(98)00057-7

Crist, E.P., Cicone, R.C., 1984. Application of the Tasseled Cap concept to simulated thematic mapper data. *Photogrammetric Engineering Remote Sensing* 50, 343–352.

Čuda, J., Rumlerová, Z., Brůna, J., Skálová, H., Pyšek, P., 2017. Floods affect the abundance of invasive Impatiens glandulifera and its spread from river corridors. *Diversity and Distributions* 23, 342–354. doi: 10.1111/ddi.12524

Dandois, J.P., Ellis, E.C., 2010. Remote sensing of vegetation structure using computer vision. *Remote Sensing* 2, 1157–1176. doi: 10.3390/rs2041157

Fuchs, R., Verburg, P.H., Clevers, J.G.P.W., Herold, M., 2015. The potential of old maps and encyclopaedias for reconstructing historic European land cover/use change. *Applied Geography* 59, 43–55. doi: 10.1016/j.apgeog.2015.02.013

Guisan, A., Weiss, S.B., Weiss, A.D., 1999. GLM versus CCA Spatial Modeling of Plant Species Distribution. *Plant Ecology* 143, 107–122. doi: 10.1023/A:1009841519580

Hais, M., Wild, J., Berec, L., Brůna, J., Kennedy, R., Braaten, J., Brož, Z., 2016. Landsat Imagery Spectral Trajectories — Important Variables for Spatially Predicting the Risks of Bark Beetle Disturbance. *Remote Sensing* 8, 1–22. doi: 10.3390/rs8080687

Haralick, R.M., Shanmugam, K., Dinstein, I., 1973. Textural features for image classification. *IEEE Transactions on Systems, Man and Cybernetics*. doi: 10.1109/TSMC.1973.4309314

Hay, G.J., Blaschke, T., Marceau, D.J., 2003. A comparison of three image-object methods for the multiscale analysis of landscape structure. *Science* 57, 327–345. doi: 10.1016/S0924-2716(02)00162-4

Jelínek, J., 2005. Od jihočeských pralesů k hospodářským lesům Šumavy. MZE ČR, Úsek lesního hospodářství, ÚHÚL Brandýs nad Labem.

Jelínek, J., 1988. Větrná a kůrovcová kalamita na Šumavě z let 1868 až 1878. Lesprojekt, Brandýs nad Labem.

Kauth, R.J., Thomas, G.S., 1976. The tasselled cap - A graphic description of the spectral-temporal development of agricultural crops as seen by Landsat. *Proceedings of the Symposium on Machine Processing of Remotely Sensed Data, West Lafayette, Indiana, U.S.A, 29 June-1 July 1976* 41–51.

Lofman, S., Kouki, J., 2001. Fifty Years of Landscape Transformation in Managed Forests of Southern Finland. *Scandinavian Journal of Forest Research* 16, 44–53. doi: 10.1080/028275801300004406

Manfreda, S., McCabe, M., Miller, P., Lucas, R., Pajuelo Madrigal, V., Mallinis, G., Ben Dor, E., Helman, D., Estes, L., Ciraolo, G., Müllerová, J., Tauro, F., de Lima, M., de Lima, J., Maltese, A., Frances, F., Caylor, K., Kohv, M., Perks, M., Ruiz-Pérez, G., Su, Z., Vico, G., Toth, B., 2018. On the Use of Unmanned Aerial Systems for Environmental Monitoring. *Remote Sensing* 10, 641. doi: 10.3390/rs10040641

McCune, B., Keon, D., 2002. Equations for potential annual direct incident radiation and heat load. *Journal of Vegetation Science* 13, 603–606. doi: 10.1111/j.1654-1103.2002.tb02087.x

METI/NASA, 2011. ASTER Global Digital Elevation Model V002.

Moudrý, V., Lecours, V., Gdulová, K., Gábor, L., Moudrá, L., Kropáček, J., Wild, J., 2018. On the use of global DEMs in ecological modelling and the accuracy of new bare-earth DEMs 383, 3–9. doi: 10.1016/j.ecolmodel.2018.05.006

Müllerová, J., Bartaloš, T., Brůna, J., Dvořák, P., Vítková, M., 2017. Metodika mapování invazních druhů pomocí dálkového průzkumu. Botanický ústav AV ČR, Průhonice. Certified by Ministry of the Environment of the Czech Republic.

Riley, S.J., DeGloria, S.D., Elliot, R., 1999. A Terrain Ruggedness Index that Qauntifies Topographic Heterogeneity. *Intermountain Journal of Sciences*. doi: citeulike-article-id:8858430

Skaloš, J., Weber, M., Lipský, Z., Trpáková, I., Šantrůčková, M., Uhlířová, L., Kukla, P., 2011. Using old military survey maps and orthophotograph maps to analyse long-term land cover changes - Case study (Czech Republic). *Applied Geography* 31, 426–438. doi: 10.1016/j.apgeog.2010.10.004

Sokal, R.R., Oden, N.L., 1978. Spatial autocorrelation i n biology 1 . Methodology. *Biological Journal of the Linnean society* 10, 199–228.

Turner, M.G., Ruscher, C.L., 1988. Changes in landscape patterns in Georgia, USA. *Landscape Ecology* 1, 241–251. doi: 10.1007/BF00157696

United States Geological Survey (USGS), 2008. Imagery for Everyone …. Reston, VA.

Vapnik, V., 1995. The Nature of statistical Learning Theory, Springer-Verlag New York. doi: 10.1007/978-1-4757-2440-0

Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J., Reynolds, J.M., 2012. “Structure-from-Motion” photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* 179, 300–314. doi: 10.1016/j.geomorph.2012.08.021

White, M., Mladenoff, D.J., 1994. Old-growth forest landscape transition from pre-European settlement to present. *Landscape Ecology* 9, 191–205. doi: 10.1007/BF00134747

Woodcock, C.E., Allen, R., Anderson, M., Belward, A., Bindschadler, R., Cohen, W., Gao, F., Goward, S.N., Helder, D., Helmer, E., Nemani, R., Oreopoulos, L., Schott, J., Thenkabail, P.S., Vermote, E.F., Vogelmann, J., Wulder, M.A., Wynne, R., 2008. Free Access to Landsat Imagery. *Science* 320, 1011a–1011a. doi: 10.1126/science.320.5879.1011a

Wulder, M.A., Masek, J.G., Cohen, W.B., Loveland, T.R., Woodcock, C.E., 2012. Opening the archive: How free data has enabled the science and monitoring promise of Landsat. *Remote Sensing of Environment* 122, 2–10. doi: 10.1016/j.rse.2012.01.010

Yokoyama, R., Shlrasawa, M., Pike, R.J., 2002. Visualizing Topography by Openness : A New Application of Image Processing to Digital Elevation Models. *Photogrammetric Engineering & Remote Sensing* 68, 257–265.

Curriculum vitae

MGR. JOSEF BRŮNA (*1984)

E-MAIL: josef.bruna@gmail.com

EDUCATION

2009 - 2018	Ph.D. program Environmental studies, Faculty of Science, Charles University, Prague.
2011	Introduction to Artificial Intelligence, online course guaranteed by Stanford University
2008 Jan-Jun	ERASMUS on University of Aarhus, Denmark, program Environmental Studies
2004 - 2009	Bc. and Msc. program Environmental protection, Faculty of Science, Charles University, Prague.

INTERNATIONAL INTERNSHIP

2012 Jan	Forest Ecosystem and Landscape Ecology Lab (David Mladenoff), Department of Forest and Wildlife Ecology, University of Wisconsin – Madison, WI, USA

WORK EXPERIENCE

2010 - now	Institute of Botany of the CAS, Průhonice – Department of GIS a RS
2012 - now	Scientific consultant at TEREZA, Educational Centre
2009 - 2011	Assistant coordinator at TEREZA, Educational Centre – in charge of an e-learning course for Projekt 3V

PROFESSIONAL KNOWLEDGE

- remote sensing and aerial imagery workflow in ArcGIS, eCognition Developer, ERDAS Imagine, Agisoft Photoscan Professional
- statistical analysis and data handling in R
- use of sub-meter GNSS with post-processing
- programming in C# .NET, Python, R
- LANDIS –II, modeling on a landscape scale – active extensions development

TEACHING

- GIS for biological applications (in Czech) Jan Wild, Josef Brůna, Matěj Man, Faculty of Science, Charles University
- Modern, practical and advanced methods in GIS (in Czech) Jan Wild, Josef Brůna, David Stella, Faculty of Science, Charles University

PARTICIPATION IN PROJECTS

2018 - 2021	UAS approach for monitoring of plant invasions over different spatial and temporal scales, principal investigator Jana Müllerová, MŠMT LTC18007.

2018 - 2020 EFI Network FORest MAnagement Scenarios for Adaptation and Mitigation (FORMOSAM), principal investigator Christopher Reyer.

2018-05 – 11 Microclimate characteristics of natural forest stages influenced by disturbances and management (contractual research for NP Šumava), principal investigator Josef Brůna.

2017 - 2021 MC Substitute of COST: CA16219 Harmonization of UAS techniques for agricultural and natural ecosystems monitoring (HARMONIOUS), principal investigator: Salvatore Manfreda

2017 – 2019 Trans-boundary mapping of forest ecosystems - Interreg Trans-boundary cooperation – Czech Republic – Free State of Bavaria, Germany, Interreg project no 99. Principal investigator since 2018.

2017 – 2019 Forest microclimate – neglected link between plant diversity and climate change. Principal investigator: Jan Wild. GAČR GA17-13998S.

2015 – 2017 Modelling of large scale multi-agents disturbances in mountain spruce forests. Principal investigator: Jan Wild, LD15158 - COST CZ.

2014 – 2017 Detection and monitoring of invasive species using UAV. Principal investigator: Jana Müllerová. TAČR TA04020455.

2014- 2018 COST: FP 1304 Towards robust projections of European forests under climate change (PROFOUND). Principal investigator: Christopher Reyer.

2014 - 2018 Excellence project: Plant diversity analysis and synthesis center (PLADIAS), principal investigator Milan Chytrý, GAČR GB14-36079G.

2012 – 2014 Wild herbivores and their impact on abandoned landscape vegetation, principal investigator Eva Horčičková, GAUK (Project 630112).

2010 – 2014 The role of disturbances in dynamics of temperate mountain spruce-dominated forests – a landscape simulation model of the Šumava Mts., principal investigator Tomáš Herben, GAČR (Project 504/10/0843).

2010 – 2012 Use of high resolution remote sensing data for modeling of tree dispersal, principal investigator Josef Brůna, GAUK (Project 20310).

2009 - 2010 Participation on project Natural dynamics of the mountain spruce forest after large disturbance: spatial explicit individual-based model, principal investigator Jan Wild. MŽP (Project SP/2D2/111/08).

PUBLICATIONS

ResearcherID: A-6601-2010
Scopus Author ID: 55798202400
ORCID ID: 0000-0002-4839-4593

Röder, M., Latifi, H., Hill, S., Wild, J., Svoboda, M., Brůna, J., Macek, M., Nováková, M. H., Gülch, E., Heurich, M. (2018). Application of optical unmanned aerial vehicle-based imagery for the inventory of natural regeneration and standing deadwood in post-disturbed spruce forests. *International Journal of Remote Sensing*, 0(0), 1–22. doi: 10.1080/01431161.2018.1441568

Müllerová, J., **Brůna, J.**, Bartaloš, T., Dvořák, P., Vítková, M., Pyšek, P. (2017). Timing Is Important: Unmanned Aircraft vs. Satellite Imagery in Plant Invasion Monitoring. *Frontiers in Plant Science*, 8(May), 1–13. doi: 10.3389/fpls.2017.00887

Čuda, J., Rumlerová, Z., **Brůna, J.**, Skálová, H., Pyšek, P. (2017) Floods affect the abundance of invasive *Impatiens glandulifera* and its spread from river corridors. *Diversity and Distributions* 23(4): 342-354. doi: 10.1111/ddi.12524

Müllerová, J., Bartaloš, T., **Brůna, J.**, Dvořák, P., Vítková, M. (2017) Unmanned aircraft in nature conservation: an example from plant invasions. *International Journal of Remote Sensing* 38(8-10):2177-2198. doi: 10.1080/01431161.2016.1275059

Štajerová, K., Šmilauer, P., **Brůna, J.**, Pyšek, P. (2017). Distribution of Invasive Plants in Urban Environment Is Strongly Spatially Structured. *Landscape Ecology*. 32(3): 681-692 doi: 10.1007/s10980-016-0480-9

Macek, M.; Wild, J.; Kopecký, M.; Červenka, J.; Svoboda, M.; Zenáhlíková, J.; **Brůna, J.**; Mosandl, R.; Fischer, A. (2017) Life and death of Picea abies after bark-beetle outbreak: ecological processes driving seedling recruitment. *Ecological Applications* 27: 156–167. doi: 2016. 10.1002/eap.1429

Hais, M.; Wild, J.; Berec, L.; **Brůna, J.**; Kennedy, R.; Braaten, J.; Brož, Z. (2016) Landsat Imagery Spectral Trajectories — Important Variables for Spatially Predicting the Risks of Bark Beetle Disturbance. *Remote Sensing* 8: 1–22. doi: 10.3390/rs8080687

Kaplan, Z.; Danihelka, J.; Štěpánková, J.; Ekrt, L.; Chrtek, J.; Zázvorka, J.; Grulich, V.; Řepka, R.; Prančl, J.; Ducháček, M.; Kůr, P.; Šumberová, K.; **Brůna, J.** (2016) Distributions of vascular plants in the Czech Republic. Part 2. *Preslia* 88: 229–322.

Brůna, J., Wild, J., Svoboda, M., Heurich, M., Müllerová, J. (2013) Impacts and underlying factors of landscape-scale, historical disturbance of mountain forest identified using archival documents, 294-306. *Forest Ecology and Management* 305. doi: 10.1016/j.foreco.2013.06.017

BOOKS CHAPTERS, BOOKS

Müllerová, J., Bartaloš, T., **Brůna, J.**, Dvořák, P., Vítková, M. (2017). Metodika mapování invazních druhů pomocí dálkového průzkumu. Botanický ústav AV ČR, Průhonice. Certified by Ministry of the Environment of the Czech Republic.

Brůna, J., Čada, V., Svoboda, M., Wild, J. (2016) Historické lesnické mapy odhalují informace o narušení lesů působením vichřice a lýkožrouta smrkového v 19. století. in Hubený, Čížková 2016 Šumavské lesy pod lupou ISBN 978-80-87257-31-9, pp 21-23.

Vojta, J., **Brůna J.**, Kubát, M., Drhovská, L. (2012) Případová studie: Doupovské hory – biodiverzita vs. velkoplošná sukcese. In: Machar I., Drobilová L. a kolektiv Ochrana přírody a krajiny v České republice Vybrané aktuální problémy a možnosti jejich řešení, část Případové studie. Univerzita Palackého v Olomouci, Olomouc.

POPULARIZATION AND PROCEEDINGS

Stella, D., **Brůna, J.**, Suske, D., Kuthan, T. (2018) Cyklistika v Praze jako základ kurzu GIS. *ArcRevue* 1/2018.

Brůna, J., Stella, D., Klimeš, A., Man, M., Kahounová, M., Wild, J. Kolik je na Šumavě nosálů? *ArcRevue* 2/2016.

Brůna, J., Vojta, J. Doupovské hory: návrat k přírodě. *Přírodovědci* 2/2016.

Müllerová, J., **Brůna, J.**, Dvořák, P., Bartaloš, T., and Vítková, M. (2016) Does the data resolution/origin matter? Satellite, airborne and UAV imagery to tackle plant invasions, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B7, 903-908, doi: 10.5194/isprs-archives-XLI-B7-903-2016, 2016

Dvořák, P., Müllerová, J., Bartaloš, T., **Brůna, J.** (2015) Unmanned aerial vehicles for alien plant species detection and monitoring, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-1/W4, 83-90, doi:10.5194/isprsarchives-XL-1-W4-83-2015

Kolektiv autorů (2014) Metodické materiály Badatelé.cz. Praha http://www.badatele.cz

Čada, V., **Brůna, J**., Svoboda, M., Wild, J. Dynamika horských smrčin na Šumavě. *Živa* 5/2013.

Čada, Svoboda, Janda, Rejzek, Bače, Wild, **Brůna** (2013) Původ a historie narušení horských smrčin Šumavy – předběžné výsledky. Sborník z konference Lesník 21. století. 9 pages.

Brůna, J.; Semeráková, B. (2011) Towards Science and Research. In Multi-Actor Learning for Sustainable Regional Development in Europe: A Handbook of Best Practice, editors Andrew Barton & Jana Dlouhá. p 247 - 264. Grosvenor House Publishing Ltd. ISBN 978-1-908105-33-2.

Brůna, J. (2012) Use of high resolution remote sensing data for modelling of tree dispersal. in Modelling Forest Ecosystems – Concepts, Data and Application Proceedings of the COST FP0603 Spring School, May 9th – 13th, 2011, Kaprun, Austria. Eds: Pötzelsberger, Mäkelä, Hasenauer, Mohren, Palahí, Tomé. Universität f. Bodenkultur, Wien. ISBN 978-3-900962-98-2.

Červenka, J., Wild, J., Svoboda, M., Kopecký, M., Macek, M., **Brůna, J.**, Zenáhlíková, J. (2011) The state of the natural regeneration in Bavarian Forest National Park, 10 years after the total death parent stands. ISBN: 978-80-213-2086-1; 279 pages; ČZU in Prague; COYOUS 2011.

Zajíčková, L., **Brůna, J.**, Vojta, J., Kopecký, M., Klagová, Z. (2011) Od zemědělské krajiny k novodobým pralesům. *Živa* 4/2011.

Brůna, J. (2010) E-learningový kurz Projektu 3V - Vědě a výzkumu vstříc. In Alternativní metody výuky 2011, sborník příspěvků, editors Miroslav Ulrich & Karel Zatloukal GAUDEAMUS Hradec Králové, ISBN 978-80-7435-104-4.

Brůna, J. (2010) Modelování změn krajinného pokryvu v opuštěné krajině s využitím série leteckých snímků. Sborník z konference SGP 2010. Arcadata, Praha ISBN 978–80–904450–3–1, 80-87.

Kolektiv autorů (2010) Metodické materiály Projekt3V - Vědě a výzkumu vstříc. Praha. http://www.projekt3v.cz/

CONFERENCE CONTRIBUTIONS

10 presentations, 14 posters

- Geologisk symposium (2008) Aarhus, Denmark (presentation)
- 17th conference GIS ESRI v ČR (2008) Praha (poster)
- IGU-LUCC Conference (2010) „Land use and land cover changes in a globalised world“, Praha (presentation)
- Student GIS Projekt (2010), Kozel (presentation)
- New approaches in land cover/use change research (2010), Praha (presentation)
- Frontiers in Historical Ecology (2011) Zürich, Switzerland (poster)
- Spatial Ecology & Conservation (2011) Birmingham, Great Britain (presentation)
- EARSeL-Temporal Analysis of Satellite Images (2012) Mykonos, Greece (poster)
- ECCB - European Congress of Conservation biology (2012) Glasgow, Scotland, UK (presentation)
- 21st conference GIS ESRI v ČR (2012) Praha (poster)

- Natural Disturbance Conference (2013) Neuschönau, Germany (poster)
- 56th IAVS conference (2013) Tartu, Estonia (poster)
- GEOBIA (2014) Thessaloniki, Greece (presentation)
- FORDISMAN (2014) Tartu, Estonia (poster)
- 23rd conference GIS ESRI v ČR (2014) Praha (poster)
- Praktické využití GIS v lesnictví a zemědělství (2015), Brno (presentation)
- 6th ESA Advanced Training Course on Land Remote Sensing (2015), Bucharest, Romania (poster)
- 24th conference GIS ESRI v ČR (2015) Praha (poster)
- Living Planet Symposium (2016) Praha (poster)
- GEOBIA (2016) Enschede, Netherlands (poster)
- 25th conference GIS ESRI v ČR (2016) Praha (presentation, poster)
- EMAPI 14 (2017) Lisbon, Portugal (presentation)
- 26th conference GIS ESRI v ČR (2017) Praha (poster)

Selected publications

1. Publications used in dissertation

a. with IF

Brůna, J., Wild, J., Svoboda, M., Heurich, M., Müllerová, J. (2013) Impacts and underlying factors of landscape-scale, historical disturbance of mountain forest identified using archival documents, *Forest Ecology and Management* 305:294-306. doi: 10.1016/j.foreco.2013.06.017 (referred in text as **Paper I**)

- IF 2016: 3.064; Citations 27 (Google Scholar)

Hais, M.; Wild, J.; Berec, L.; **Brůna, J.**; Kennedy, R.; Braaten, J.; Brož, Z. (2016) Landsat Imagery Spectral Trajectories — Important Variables for Spatially Predicting the Risks of Bark Beetle Disturbance. *Remote Sensing* 8: 1–22. doi :10.3390/rs8080687 (referred in text as **Paper III**)

- IF 2016: 3.244; Citations 3 (Google Scholar)

Müllerová, J., Bartaloš, T., **Brůna, J.**, Dvořák, P., Vítková, M. (2017) Unmanned aircraft in nature conservation: an example from plant invasions. International Journal of Remote Sensing 38(8-10):2177-2198. doi: 10.1080/01431161.2016.1275059 (referred in text as **Paper IV**)

- IF 2016: 1.724; Citations 10 (Google Scholar)

Müllerová, J., **Brůna, J.**, Bartaloš, T., Dvořák, P., Vítková, M., Pyšek, P. (2017). Timing Is Important: Unmanned Aircraft vs. Satellite Imagery in Plant Invasion Monitoring. *Frontiers in Plant Science*, 8(May), 1–13. doi: 10.3389/fpls.2017.00887 (referred in text as Paper V)

- IF 2016: 4.298; Citations 11 (Google Scholar)

b. without IF

Brůna, J., Vojta, J. (*manuscript*) Landscape-scale forest succession on abandoned agricultural land is controlled by terrain topography, distance to seed source and previous land use (referred in text as **Paper II**)

- prepared for a journal with IF

2. Publications not used in dissertation covering the same topic

a. with IF

Röder, M., Latifi, H., Hill, S., Wild, J., Svoboda, M., **Brůna, J.**, Macek, M., Nováková, M. H., Gülch, E., Heurich, M. (2018). Application of optical unmanned aerial vehicle-based imagery for the inventory of natural regeneration and standing deadwood in post-disturbed spruce forests. *International Journal of Remote Sensing*, 0(0), 1–22. doi: 10.1080/01431161.2018.1441568

Čuda, J., Rumlerová, Z., **Brůna, J.**, Skálová, H., Pyšek, P. (2017) Floods affect the abundance of invasive Impatiens glandulifera and its spread from river corridors. *Diversity and Distributions* 23(4):342-354 doi: 10.1111/ddi.12524

Štajerová, K., Šmilauer, P., **Brůna, J.**, Pyšek, P. (2017). Distribution of Invasive Plants in Urban Environment Is Strongly Spatially Structured. *Landscape Ecology*. 32(3): 681-692 doi: 10.1007/s10980-016-0480-9

Macek, M.; Wild, J.; Kopecký, M.; Červenka, J.; Svoboda, M.; Zenáhlíková, J.; **Brůna, J.**; Mosandl, R.; Fischer, A. (2017) Life and death of Picea abies after bark-beetle outbreak: ecological processes driving seedling recruitment. *Ecological Applications* 27: 156–167. doi: 2016. 10.1002/eap.1429

Zdeněk Kaplan; Danihelka, J.; Štěpánková, J.; Ekrt, L.; Chrtek, J.; Zázvorka, J.; Grulich, V.; Řepka, R.; Prančl, J.; Ducháček, M.; Kůr, P.; Šumberová, K.; **Brůna, J.** (2016) Distributions of vascular plants in the Czech Republic. Part 2. *Preslia* 88: 229–322.

b. without IF

Müllerová, J., Bartaloš, T., **Brůna, J.**, Dvořák, P., Vítková, M. (2017) Metodika mapování invazních druhů pomocí dálkového průzkumu. Botanický ústav AV ČR, Průhonice. Certifikováno MŽP.

Müllerová, J., **Brůna, J.**, Dvořák, P., Bartaloš, T., and Vítková, M. (2016) Does the data resolution/origin matter? Satellite, airborne and UAV imagery to tackle plant invasions, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLI-B7, 903-908, doi: 10.5194/isprs-archives-XLI-B7-903-2016

Dvořák, P., Müllerová, J., Bartaloš, T., and **Brůna, J.** (2015) Unmanned aerial vehicles for alien plant species detection and monitoring, *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-1/W4, 83-90, doi: 10.5194/isprsarchives-XL-1-W4-83-2015

Brůna, J., Čada, V., Svoboda, M., Wild, J. (2016) Historické lesnické mapy odhalují informace o narušenní lesů působením vichřice a lýkožrouta smrkového v 19. století. in Hubený, P., Čížková, P. Šumavské lesy pod lupou. Správa NP Šumava 2016, ISBN 978-80-87257-31-9, 129 stran. pp 21-23.

Vojta J., **Brůna J.**, Kubát M., Drhovská L. (2012) Případová studie: Doupovské hory – biodiverzita vs. velkoplošná sukcese. In: Machar I., Drobilová L. a kolektiv Ochrana přírody a krajiny v České republice Vybrané aktuální problémy a možnosti jejich řešení, část Případové studie. Univerzita Palackého v Olomouci, Olomouc.

Brůna, J. (2012) Use of high resolution remote sensing data for modelling of tree dispersal. in Modelling Forest Ecosystems – Concepts, Data and Application Proceedings of the COST FP0603 Spring School, May 9th – 13th, 2011, Kaprun, Austria. Eds: Pötzelsberger, Mäkelä, Hasenauer, Mohren, Palahí, Tomé. Universität f. Bodenkultur, Wien. ISBN 978-3-900962-98-2.

Contents