Summary

Temperate mountain forests are ecologically unique ecosystems that are particularly vulnerable to climate change and its negative effects. Changes in precipitation, higher temperatures, or more severe droughts can significantly affect mountain forest health and increase the susceptibility to disturbances and dieback. Monitoring these forests and providing information about them is therefore essential to mitigate the negative effects of climate change. Information on forest properties, such as species composition, trees age, stand structure, and disturbances, is important in a variety of studies, such as biodiversity analysis, biomass and carbon estimation, fire and drought risk monitoring, but also in forest management. Carpathian forests are an example of forest ecosystems of exceptional ecological value, and they represent the largest temperate forest ecosystem in Europe. The use of satellite remote sensing data can be an effective tool for acquiring up-to-date information about these ecosystems.

In recent years, with the launch of the Sentinel-2 mission, unprecedented opportunities in analyzing forest characteristics have arisen. The Sentinel-2 imagery is characterized by high spatial, spectral, and temporal resolutions, and it enables a more accurate analysis of forest stand characteristics. However, the potential of Sentinel-2 data, especially in regional scales and mountainous areas, is still not fully explored. There is also a need to develop and test automatic processing and analyzing approaches, that will effectively deal with large and high-dimensional datasets and mitigate the impact of, e.g., frequent cloud cover on the results.

This dissertation aimed to evaluate the usefulness of the remote sensing data, specifically the time series of Sentinel-2 imagery, in determining temperate mountain forest characteristics. The objectives of this dissertation were verified for the area of the Polish Carpathians, characterized by a significant share of forest cover and diverse species composition, as well as a high variability of environmental conditions. The aim was to identify the stand properties, including species composition, age, stand density, and crown closure, and their influence on the stand reflectance. Additionally, the relationships between stands reflectance and the environmental conditions were assessed. It was evaluated which spectral bands and which dates are crucial in determining forest properties. A number of methods were tested in this study, including generation of spectral-temporal variables, machine learning methods (ML), variable importance assessment, ensemble approach, and generalized additive models (GAM).

In the first article included in this dissertation, the dense time series of 18 Sentinel-2 images were assessed in the stand species classification for the area of the Baligród forest district in the Bieszczady Mountains. In the second article, three ML methods were assessed in the classification of species composition for the entire Polish Carpathians mountains. In the last, third article, it was determined how other properties, i.e. stand characteristics and site conditions, influence the stand reflectance, for the area of eastern Polish Carpathians and the Outer Subcarpathia.

The results of this dissertation demonstrated the usefulness and versatility of Sentinel-2 imagery in mapping forest stand species composition and analyzing other forest properties in a large, mountainous region. The use of multi-temporal data from different seasons was crucial in identifying the species composition and other stand properties. Sentinel-2 bands from the near-infrared (NIR), short-wave infrared (SWIR), red-edge, and visible red ranges had the highest contribution in analyzing forest species composition and other stand properties such as the type of understory vegetation. In the classification of species composition using three ML methods: Random Forest (RF), Support Vector Machines (SVM), and Extreme Gradient Boosting (XGB), the SVM algorithm provided the highest classification accuracies. In the stand species classification of mountainous areas, apart from spectral variables, there was a significant role of the elevation layer, with the highest contribution for mapping the species following natural height gradients. Combining the results of different models in the ensemble approach, provided valuable information on the precision of classification. In modeling the relationships between stand and environmental properties and the stand reflectance, GAM was a flexible and interpretable method, useful in analyzing the impact of multiple predictor variables on stand reflectance. Besides species composition, other factors can significantly influence stand reflectance. The influence of elevation, which is strongly coupled with local microclimate and therefore, the timing of phenophases, was particularly high in the case of beech stands reflectance. This impact differed depending on the analyzed band and dynamically changed in spring and autumn. On the other hand, stand reflectance in the case of conifer species largely depended on properties such as stand density (Scots pine) and age (Silver fir).

The results of this dissertation contribute to the research on the use of multi-spectral satellite data in the temperate mountain forests analysis, carried out for the test area of the Polish Carpathians. The conducted research confirmed the usefulness of the Sentinel-2 time series in determining the characteristics of forests. Sentinel-2 imagery is an excellent source of information on forest ecosystems, and there is no doubt that in the future, these data will help

to monitor and understand the changes in the environment at broad spatial scales. The use of longer Sentinel-2 time series in future studies will provide invaluable information, for example, that will serve as an indicator of vegetation phenology responses to climate change. The methods and approaches developed in this dissertation are ready to be potentially integrated into operational programs focused on forest monitoring at the local and regional scales.