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学　位　論　文　要　旨

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題目: Multispectral Profiling and Genetic Analyses of Seasonal Transformation in *Phedimus* Greening Plants

（*Phedimus*属緑化植物における季節的形態変化のマルチスペクトルプロファイリングと遺伝学的解析）

For perennial ornamental plants, year-round appearance is important. Among ornamental plants, *Phedimus takesimensis* has been used as a rooftop plant in Japan. Plants in the *Phedimus* genus of the family Crassulaceae are perennial, and seasonal changes in color and form occur throughout the year. Dormancy is broken in early spring, vigorous growth occurs from spring to early summer, growth ceases around summer, leaf senescence occurs after that, and defoliation occurs in autumn. At the time of defoliation, new shoots have already formed at the base of the plant, and these shoots are exposed by defoliation. Most plants in the genus *Phedimus* are winter dormant, meaning that shoots differentiate in the fall and overwinter as rosette-like shoots throughout the winter. *P. takesimensis* is less winter dormant (evergreen), and its autumn-differentiated shoots overwinter with a certain degree of elongation and development. Both the winter dormant and evergreen lines break dormancy the following spring, and the shoots begin to grow vigorously. Good appearance is important for ornamental plants, and plant color is a factor that greatly affects appearance. A multispectral camera can measure the intensity of multiple types of visible and invisible light reflected from the plant body. Furthermore, various vegetation indices calculated from the wavelength values can provide information on the degree of growth activity and other factors to estimate the state of the plant. Therefore, it seemed that multispectral image analysis would be suitable for measuring and evaluating seasonal changes in appearance, such as changes in color and growth activity, in *P. takesimensis*. However, there are few such studies on perennial ornamental plants. Also, genetic studies have not been well conducted on plants of the genus *Phedimus*, including *P. takesimensis*.

In this study, parent 1 (P_1), an evergreen (low winter dormancy) individual of *P. takesimensis*, and Parent 2 (P_2), a dormant (high winter dormancy) individual of *P. takesimensis*, and 94 individuals of the F_1 population produced from them as parents, were used for multispectral image analysis and QTL analysis.

April is the time when dormancy breaking occurs, which is the most significant morphological change of the year. In Chapter 2, the phenotypes of the P_1, P_2 and F_1 populations were investigated by multispectral image analysis in April 2019 and April 2020. Multispectral image analysis yielded cover area of individual plants, 9 wavelength values reflected from the plants, and 15 vegetation index values calculated from the wavelength values. PCA based on wavelength values showed that the contribution of PC1 was quite high, approximately 90%, reflecting visible light, indicating that multispectral image analysis is suitable for evaluating plant body color. There was a correlation between cover area at dormancy break (i.e., the earliness of dormancy break) and plant color, indicating that individuals with higher cover area had greener plant bodies. Since the annual correlation was high for many trait values except for the 800 nm reflectance value, it was inferred that this measurement method is also highly reproducible. In summary, multispectral image analysis was found to be a suitable method for quantitatively evaluating the visible color of plants and the degree of dormancy breakthrough. In this study, the first linkage map for *Phedimus* species were

also produced. QTL analysis revealed two QTLs (LG-34.P_2 and LG-7.P_1) that appeared to be related to dormancy breaking. Based on the genotypes of the nearest neighbor markers of these two QTLs, the F_1 population was grouped. Subsequently, a comparison was conducted among the groups regarding vegetation index values (VARI and SR) related to biomass. The analysis revealed significant differences in the trait values among the groups. Furthermore, differences in visual plant appearance, such as cover area and color, were also observed between genotype groups. This suggested that these two QTL are involved in the earliness of dormancy breakthrough. Of the two QTL, the LG-34.P_2 QTL was seen over a two-year period, suggesting a large effect. The QTL of LG-34.P_2 and LG-7.P_1 were observed in different traits, suggesting that each of these QTL may be involved in dormancy breaking through different functions.

However, observation of only one point in time in April does not provide a sufficient picture of seasonal changes over time, such as changes in color and growth activity throughout the year. Therefore, in Chapter 3, a total of 16 multispectral image analyses were conducted approximately every month for a year, from March 2019 to April 2020, using the measurement method established in Chapter 2. Since the beginning of the measurements in March 2019, the respective values of the vegetation index and PCA gradually changed with seasonal changes, and by the end of the measurements in the following April 2020, the values were close to those in March 2019. There were two major types of vegetation indices: vegetation indices related to biomass, which tended to be high during the growing season, and vegetation indices related to anthocyanins, which tended to be high during the dormant season. It was found that the temporal measurement methods used in this study better captured seasonal changes in color and growth activity of *P. takesimensis*. Furthermore, QTL analysis performed on the basis of each trait value on each measurement date revealed seven major QTL. These QTL tended to appear when major morphological changes occur, such as when dormancy is broken or during growth. In particular, the largest number of QTL (3 out of 7) were found during dormancy breakthrough, when the most significant morphological changes occur during the year. Among the QTL found during dormancy breakthrough, the QTL for LG-34.P_2 was presumed to be the most effective QTL because it had the highest number of traits that produced QTL during the year. Furthermore, this QTL was the only one that commonly appeared across years in spring 2019 and spring 2020, so it appeared to be highly reproducible. Even if the LOD values did not exceed a significant threshold, chromosomal sites with relatively high LOD values tended to appear continuously and seasonally on multiple measurement dates. The characteristics of F_1 were closer to those of P_2 than to those of P_1 throughout the year, and this trend was particularly pronounced during the dormant winter season. For example, during the winter season, the vegetation index for biomass was higher in P_1, while the vegetation index for anthocyanins was higher in P_2 and F_1. These vegetation index values suggest that it is possible to quantitatively assess the degree of dormancy.

The multispectral image analysis-based measurement method used in this study allowed us to successfully evaluate the plant color of *P. takesimensis*, the rapidity of dormancy breakthrough, and the seasonal changes in color and growth activity throughout the year, quantitatively and over time. In addition, QTL that may be related to seasonal morphological changes, including dormancy breakthrough, were found. It was found that seasonal changes could be better captured by multispectral image analysis over time, rather than measuring only temporal points. The measurement and evaluation methods presented in this study could be used not only for the genus *Phedimus*, but also for other plants.