Thesis of Doctoral (Ph.D.) dissertation

APPLICATION OF SPECTRAL INFORMATION IN PRECISION FRUIT PRODUCTION

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1. BACKGROUND AND AIMS OF THE DISSERTATION

Production of appropriate quality and quantity horticultural products are provided by excellent agro-ecological conditions, which are derived from the location of Hungary. Among of produced fruit species in Hungary, the pome fruits, which cover one of the largest area in our country. From the mid-80s, the Hungarian apple plantations were being decreased continuously up to 2000s when this reduction was moderated, respectively it started to stagnate due to creating new intensive plantations (GONDA and APÁTI 2011).

Building of water-, energy- and pesticide-saving systems are important development directions in the area of traditional cultivation techniques, although, in the case of this cultivation techniques the experimental area is treated as a homogeneous unit. To enhance the efficiency of the novel precision horticultural systems, numerous new information have to be used. The field acquired information serves more and more detailed spatial and a temporal knowledge, in this way it provides basic data to develop cultivation technique and to enhance the competitiveness of apple production.

Presently, due to the fast development of information systems, special instruments and range of various services are available. All achievements of information technology and information society are integrating continuously in to the modern production systems. Thus, precision agriculture can combines global positioning system (GPS), global information system (GIS) and remote sensing (RS) in a uniform and a complementary system, with which contribute to develop modern and effective cultivation techniques. In the point of view of precision farming, the development of different technologically elements provide the survey of environmental condition, vegetation analysis, monitoring of biomass changing, overall all natural processes in plantations. Developed sensors allow faster and more accurate measurements. Due to the higher spatial resolution, the information content of data become much higher, which require newer processing methods. In order to execute the given tasks – from data acquisition to interpretation of results – often very serious hardware and software environment are needed.

The aim of my work details

Overall objective of my research was investigation of spectral and structural features of an intensive apple orchard; effective separation and identification of spatial and temporal changing in characteristics of the orchard in all growing season. The measurements were primarily carried out with active and passive remote sensing instruments. In order to evaluate some determinant factors of water consumption in the orchard, I prepared detailed examinations, such as tendency and classification of weed coverage, as well as to analyze of moisture conditions of soil surface.

Detailed investigational aims:

- To execute reference positioning examination.
- To describe the material quality and spatial structure of the investigated apple orchard – such as a plant production space – with remote sensing instruments.
- To define the ecological environment in more accurate manner
- To investigate the horticultural applicability of terrestrial remote sensing methods
- To evaluate remote sensing based yield investigation, primarily in the area of fruit ripening and fruit mass estimation.
- To execute the weed detection and species-level weed segmentation
- To evaluate the soil surface moisture condition and the characteristics of micro relief

2. RESEARCH METHODS

Introducing of research sites

The researches were carried out in two different sites. Spectral and 3D laser surveys were executed at the Study and Regional Research Farm of the University of Debrecen, nearby Pallag. Reference localization investigations, with GPS correction signals, were executed in one of arable land at the Helianthus Növénytermelő, Szolgáltató és Kereskedelmi Kft.

The study area, where the terrestrial remote sensing data was acquired, was an intensive apple orchard with a drip irrigation system, which is situated at the northern part of the Study and Regional Research Farm of the University of Debrecen. My examinations focused on a smaller part (0.1 ha) of the whole orchard (0.6 ha), which were planted in 2006. The smaller area is protected by hail net. The hail protected plantation consists of 6 rows, each row is 50 m long in 4x1 m tree spacing. Considering the spatial distribution, different apple tree varieties on M9 rootstock are planted (two rows *Golden Reinders*, two rows *Early Gold*, one row *Gala Galaxy* and one row *Gala Must*) on the test site.

Introduction of localization and guidance examinations

Localization and automatic guidance investigations were carried out at an arable field (physical block ID number: JJRDJ-5-09), of the Helianthus Növénytermelő, Szolgáltató és Kereskedelmi Kft. nearby Adony. Measurement was performed between 11-17 August, 2011. The steering accuracy of a New Holland T 6030 tractor, installed with Trimble Autopilot (Trimble Navigation Limited, Sunnyvale, CA, USA) hydraulic robot pilot system and controlled by a Trimble FmX display (Trimble Navigation Limited, Sunnyvale, CA, USA) was investigated. The test tractor was installed with two FmX displays. Either of them (FmX_1) have recorded the positioning data and the other one (FmX_2) have done the guidance. Test swats were marked out on a 130 m long straight sections after the turns in North–South and East–West directions. Autopilot was used for following the same test AB lines there and back in 10 repetitions in North–South, South–North, East–West and West–East directions. Repetitions were done from each direction using different GPS correction signals such as no correction (No CORR), EGNOS, OmniStar VBS, OmniStar HP, RTK from own base station and network RTK (GNSS), in order to investigate, which corrections can serve the most effective automatic guidance.

Examination of fruit tree canopy and weeds using vegetation index meter

Spectral investigation of the canopy were carried out by terrestrial remote sensing instruments.

Vegetation analysis were executed by GreenSeeker 505 sensor (NTech Industries, Inc., Ukiah, CA, USA). The instrument belong to the family of active remote sensing devices with own illumination, therefore it can be used day or night. The instrument emits red (RED – 656 nm) and near infrared (NIR – 774 nm) lights. Reflected radiation from the canopy surface is focused by round window in a detector, where 5 different vegetation indices are calculated. The calculated vegetation indices are correlated with each other tightly. The used vegetation index was the NDVI (*Normalized Difference Vegetation Index*).

The surveys were performed from 70-110 cm operation range from the object, based on the user manual data of the sensor. Primarily, the instrument was developed to survey field conditions. The instrument was rotated by 90°, thus data was collected parallel with the rows under horticultural circumstances. Since, operational guide was not available for such different application, data collection features were determined by field and laboratory tests.

Based on the laboratory tests and the factory manual, the surveys were carried out evenly spaced (ca. 0.8-1 m) from the surface. The AgGPS FmX onboard computer was used to collect and synchroniz the data. AgGPS FmX was the user interface of GreenSeeker, which was mounted on the tractor. Speed of a tractor was uniform under the measures, which is proved by the relative low standard deviation values. For detailed vegetation analysis, the hardware of job computer was stored acquired data (GPS coordinates and other important position data) in each second. This positioning data was synchronized with NDVI data. Data processing was carried out in Surfer 11 (Golden Software, Inc., Golden, CO, USA) software environment.

Multispectral imaging system

In order to analyze the weed and cultivated plant, Tetracam (Tetracam, Inc., Chatsworth, CA, USA) broadband multispectral imaging system had to be used. Combine the tree spectral bands (green – 520-600 nm, red – 650-750 nm, infrared – 750-950 nm) of the camera, different vegetation indices were created to investigate the vegetation activity. The digital camera have a 1.3 megapixels (Motorola CMOS) detector, with a 1280x1024 pixel resolution. Canopy of fruit trees and the spacing of the orchard were surveyed by this cam. Data processing and digital image analysis were performed by PixelWrench2 (Tetracam, Inc., Chatsworth, CA, USA) and IDRIS Taiga (Clark Labs, Clark University, Worcester, MA, USA) software.

Laboratory spectrometer

Fruit ripening of two apple varieties (red covering colored *Gala Must* and yellow skin colored *Early Gold*) was examined by Avantes AvaSpec 2048 Fiber Optic Spectrometer. Considering ripening stages and harvest time of the varieties, in 6 and 7 dates were collected and measured the fruit samples. Ripening processes were evaluated by PSRI (*Plant Senescence Reflectance Index*) and BRI (*Browning Reflectance Index*) vegetation indices.

Measurement range of the instrument is 400-1000 nm, the spectral resolution is 0.566 nm and the accuracy is 1 nm. The AvaSpec 2048 system consists of a spectrometer (detector) and connected by an 8 μm core diameter fiber optic standard AvaLight-HAL halogen light source. The light source has about 1 μWatt light energy input to result the permanent light intensity in the whole measure range. The accurate measurement was provided by a special spectral sampling back box, since the samples were isolated from the variable external electromagnetic radiation.

3D terrestrial laser scanner

Investigation of fruit trees, structural examination of weed flora and micro relief analyzing of the soil surface were carried out by Leica ScanStation C10 (Leica Geosystems AG, Heerbrugg, Switzerland) terrestrial laser scanner. Surveying of fruit orchard and those surrounding by 3D laser scanner have not been done so far in Hungary. In the international literature could be even found mainly forestry investigations (PFEIFER et al., 2004; DASSOT et al., 2011; SEIDEL et al., 2011).

The ScanStation C10 by Leica Geosystems uses the time-of-flight (TOF) principle for ranging. The scanner sweeps along the examined object with a green (532 nm) laser light, while measures the distances of several thousand points per second (up to 50,000 points/sec), creating a high resolution point cloud which ensure the 3D structural data of objects. The laser beam deflection is occurred by a Smart X-Mirror™. Thus a point cloud, which consist of millions of points was created only from one scan station. In order to create the high quality virtual reconstruction of the trees with the apple fruits, primary condition is the using of more scan stations with overlapping.

The beam divergence is 0.1 mrad; which means that the diameter of laser point is 10 mm on 100 m. This source of error is – in case of maximal measurement distance (on 300 m) –

only 3 cm. During the measurement, this source of error was considering. So, the surveys were worked out by 15 scan stations. Overlapping of scanning areas provided the unifying of point clouds, and increased the accuracy of measurement.

Based on the laser scanned data, structural parameters of the whole plantation and fruits were examined. Trunk diameter of apple trees, furthermore maximum height and maximum width of selected fruits were measured by traditional slide-caliper. Trunk diameter measurements were executed between the root collar and the first branch. Trunk diameter determination from laser data was similar height than measurement with slide-caliper. Preprocessing of the point cloud was performed by Leica Cyclone 7.1 software (Leica Geosystems AG, Heerbrugg, Switzerland), after exporting of point cloud in appropriate format, post processing was carried out in 3DReshaper (TECHNODIGIT – Hexagon group, Genay, France) and Geomagic Studio 12 (Geomagic, Inc., Raleigh, NC, USA) software environments.

Laser scanner based yield mass examination was carried out with *Gala Galaxy* variety. Primarily, such fruits were selected, which were localized in greater or lesser fruit groups. Maximum height and maximum width of fruits were measured with slide-caliper on the field. After that weight and the density of fruits were determined under laboratory conditions. Fruit density was calculated based on water displacement principle. Fruits were immersed into a measuring cylinder whose volumetric size was 2 liter, and we cared to cover the fruits with water. Based on the rise in water level, density of fruits were defined. Weight determination of virtual fruits were worked out by fitting algorithm (least squares method) in post processing software. I defined spherical volume, which simulated fruits with helping of sphere as the best fitting form for the point cloud curvature. After that, based on calculated density spherical volume, I counted the weight. In some cases, majority of the point cloud was shadowed by the leaves and branches. Nevertheless, based on the curvature of the point cloud, applied software (Leica Cyclone, Geomagic, 3DReshaper, CloudCompare) was ideal to shape fitting.

Overmoisturing investigation of soil surface with laser scanner

Depending on the wavelength, water can absorb laser beam. Shorter wavelengths (blue and green) transmit through to water, while infrared light reflects from the water surface (HECKMAN and HODGSON 1967; FUNK et al., 1972; MOORE et al., 2000). Due to increasing of saturation of the soil, reflectance properties of laser beam are changing, however intensity value of laser light is influenced by distance of laser scanner and the soil surface. Laboratory tests and field measurements were worked out to examine that the distance what extent is influenced by the laser intensity. In order to detect the moisture content of the soil surface, applicability of laser scanner were used from varying distances and angular resolution under laboratory conditions. Sandy soil samples were collected from the 10 cm layer of the examined area. The samples were dried to constant weight at 105°C, then rewetting to different moisture. After that, the soil was watered again, separated in different (as 2% steps by weight) moisture contain to 32% in petri dishes. These samples were placed in three different distance (4 m – 26.47°, 6.5 m – 17.23° and 9 m – 12.63°) from the laser scanner. In the case of laboratory test, two resolutions (millimeter and centimeter) were applied. Each petri dish was separated from the laser point cloud, then the laser impulse data was analyzed by ANOVA. Tukey's test was used for pairwise comparisons. Statistically separability of soil samples were examined by this Post Hoc analysis. Number of reflected laser lights were decreased, depending on distance and resolution. In the case of millimeter resolution, average "size" of point cloud was more than 3200 pts/petri dish at 4 m. Soil samples, which were 6.5 m from the scanner, had 25% less points. In the case of centimeter resolution, the point clouds were unsuitable to separate visual the petri dishes. Due to the low resolution (ca. 32 pts/petri dish), another technique was used for the evaluation. Based on the high resolution point cloud data, cropping areas were created, then the gridded model – prepared from the low resolution point cloud with Kriging method in Surfer 11 – was separated and analyzed. After that, using certain moisture categories – as training sites –, laser based soil surface data was classified in different software environments (Global Mapper 15.0, IDRISI Taiga).

3. MAIN OBSERVATION OF DISSERTATION

Production of high quality horticultural crops, require the site-specific management techniques from the farmers, which can be provided by high tech IT instruments. I had possibility to investigate spectral and structural characteristics of an intensive apple plantation, by means of GIS and remote sensing systems, which are less used in horticultural area.

In order to analyze the real time positioning on the field, localization examinations were carried out. Free of charge (No CORR and EGNOS) and subscription-based systems (OmniStar VBS, OmniStar HP, RTK and GNSS) with different directions were used to evaluate the GPS based automatic guidance system of the tractor. Offline distance (average steering error) values were saved by the AgGPS FmX integrated display. Furthermore, offline distance values were classified into intervals of tenth of a meter, then the number of intervals were summarized to quantify the navigate accuracy of each examined correction (*Figure 1*). According to the compering investigation, the most inaccurate results derived from the No CORR test. No CORR measurements significantly differed from the measurement, which used various corrections.

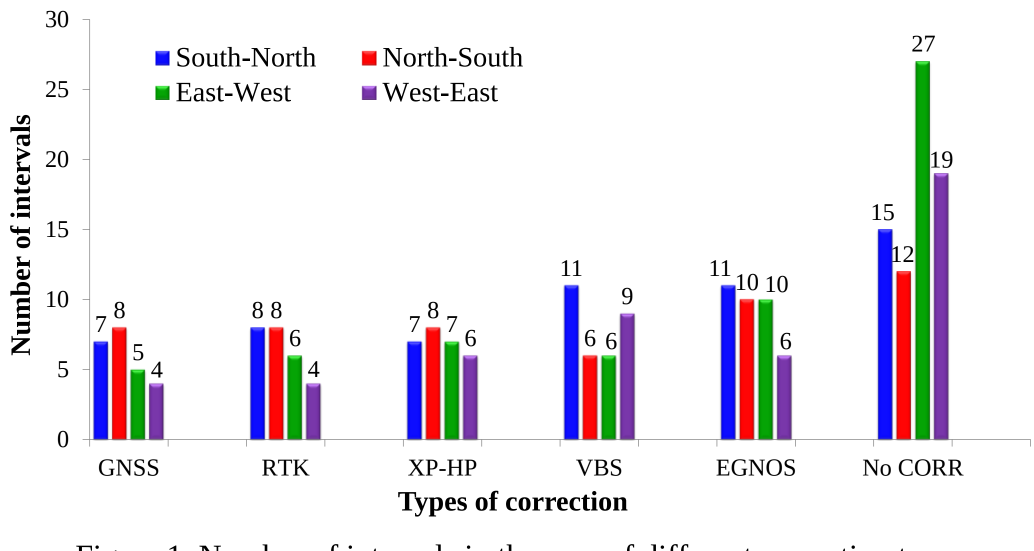

Figure 1. Number of intervals in the case of different correction types

Spectral investigations were carried out in different phenological stages of fruit trees canopy development. Before the field measurement, the laboratory calibration curve of GreenSeeker 505 vegetation index meter was created. Spatial and temporal changes of NDVI maps were evaluated. Based on NDVI maps, infected fruit trees were discriminated before appearing chlorotic and necrotic symptoms. Furthermore, NDVI values were ideal to detect growing dynamically changes, and based on it, polynomial coherence was defined to describe this process. In order to validate the field measurements, further remote sensing instruments were used, beside the GreenSeeker 505. Strong correlations (r>0.7) were detected between the results, which were measured by different devices.

Investigation of individual structure of fruit trees were determined by 3D terrestrial laser scanner, which is less used in horticultural area. Stem diameter and height of each examined tree was measured by laser scanner as well as traditional methods. Leaf on and leaf off condition of trees were ideal for acquiring new information. In the course of analyzing of summer survey, height of tree, height and extension of canopy, stem diameter could be calculated, whereas the structure of branches were examined in the winter period. With the help of traditional and laser scanner measurements, trunk diameter of investigated trees were defined (*Figure 2.*), which were executed between the root collar and the first branch.

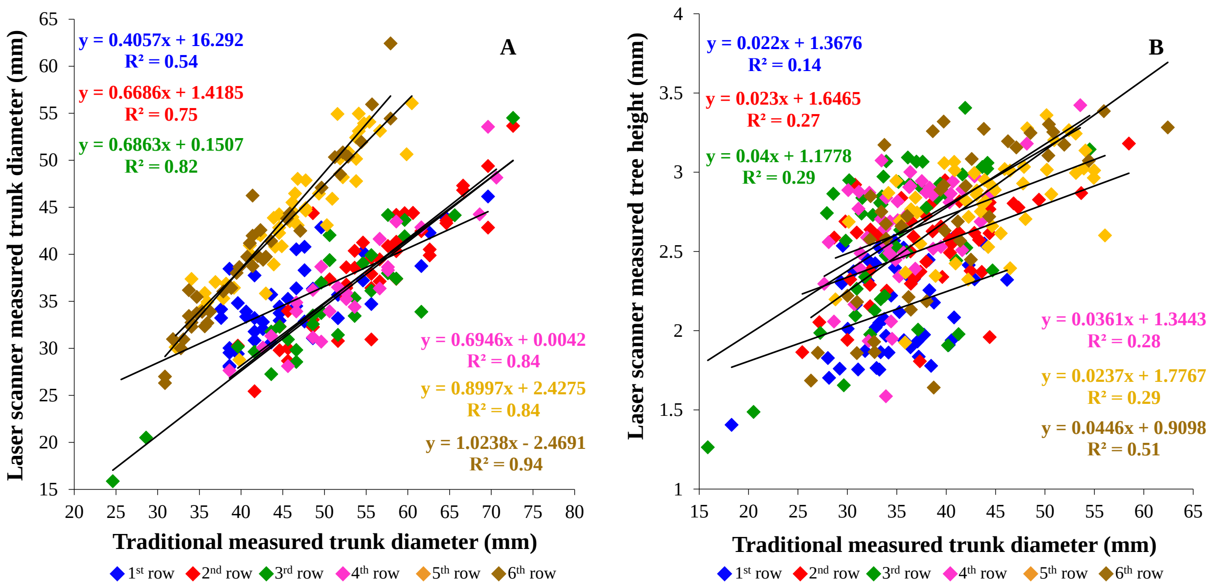

Figure 2. Comparison of traditional and laser scanner based stem diameter measurement (A) and coherences between tree height and stem diameter (B)

Coherences of stem thickness and tree height were compared (Figure 2/B). Stem circumference of trees is a complex vegetative indicator, but same stem diameters cannot betoken same tree dimensions. Beside the investigated fruit tree varieties, some anomalies (infection, mechanical damage) can cause differences in tree height, canopy extension, or bearing surface. These effects cannot be observed immediately on the trunk thickness. The average moderate correlation (r=0.59) ensued from this fact.

Yield investigation was carried out by remote sensing instruments. Ripening examination of two apple varieties (*Gala Must* and *Early Gold*) were measured by laboratory spectrometer. In the course of spectral curves analysis, those wavelengths were considering, which relate to pigment molecules in the fruit skin. Based on the wavelength, vegetation indices (PSRI, BRI) were created. Temporal change of fruit covering color was represented by parabolic function. After harvest, some fruits were let on the trees to simulate the overripening. Decay of fruits could be observed on the fruit skin, which were separability by spectral way. Spectral measures were ideal to monitor the fruit ripening. During the ripening, polynomial coherences were detected in the case of each examined variety. Vegetation indices of overriped fruits were significantly different from trend curves

3D laser point cloud was adequate to estimate the fruit weight. Fruit detection was carried out by applying spatial fitting algorithms. Then, based on the volume of fitted spheres and density of apples were calculated the weight of virtual fruits, which were strongly correlated (r=0.89) with weight of samples. Further experiments are needed to work out automatic fruit detecting; thus, the technology could appropriate to yield estimation.

Weed coverage and species-level weed segmentation of the plantation were investigated. NDVI maps – which created by GreenSeeker 505 data – were suitable for detection of spatial and temporal changes of weeds development. Measurements were completed with multispectral imaging data, then the results were statistically compared (r=0.86). Surveys were performed by digital camera too. Based on the true color images, weed coverage of the area was quantifiable with the help of a novel technique.

With reclassification of 3D laser intensity values, weed coverage of two rows were defined and species-level identification of weeds were worked out. Weed segmentation was carried out by special algorithms. The results were evaluated by ANOVA. Results can serve as basis of further investigations, which can ideal to select the monocotyledonous and dicotyledonous weeds, therefore, it can be utilized in species-specific precision weed control.

Micro relief characteristics of the investigated intensive orchard were analyzed. Beside NDVI values, the positioning data was collected by the job computer.

Based on the high density point cloud, a high precision digital elevation model was created, which represented the slope conditions of the soil more effectively. Created micro terrain model was ideal not only the inland inundation management melioration on flat (slope<5%) areas, but it could provide data for wheel rut slip and tire wear optimizing also.

Creating laboratory stepwise moisture structure was useful for training sites of 3D laser scanned field data. Changing of laser intensity values have followed the moisture content of soil in the investigated dates, which was statistically confirmed. Histogram of soil surface moisture conditions of the classified area was created. Examinations were showed that the intensity values of Leica ScanStation C10 laser scanner were influenced by distance and angle.

4. NEW SCIENTIFIC RESULTS OF DISSERTATION

1. Navigation bearing (BRG) of GPS correction systems (EGNOS, Omnistar, RTK, GNSS network operated by Institute of Geodesy, Cartography and Remote Sensing – FÖMI) was quantified under field conditions.
2. Spatial and temporal spectral changing of the investigated canopy of apple plantation were determined in the vegetation period, on this basis, polynomial coherences were created, which described the canopy development.
3. It was proved that the elaborated segmentation method of spectral spaces of intensive apple plantation is suited for early prediction of fruit tree mortality.
4. Used vegetation indices are appropriate to quantify fruit ripening, which is based on the series of spectral spot measurement of yellow (*Early Gold*) and red (*Gala Must*) skin colored apple species.
5. Based on the laser point cloud, 3D model of apple trees were defined, which model is appropriate for numerically describing of the topological structure of trees and the fruit weight estimation before harvest.
6. Laser point cloud segmentation algorithms were suitable for evaluation of spatial structure of weed flora. Results were validated by different remote sensing techniques.
7. Runoff conditions of the apple plantation were evaluated by digital terrain model. Furthermore, it was determined that the green (532 nm) laser return intensity values were ideal to evaluate the moisture conditions of soil surface.

5. PRACTICAL UTILIZATION OF RESULTS

1. Used spectral instruments and GIS techniques could provide opportunities for further develop of herbicide saving, site- and species-specific weed control in precision horticultural systems.
2. Early pathological detection can help for the farmers to optimize the preventive plant protection.
3. Used vegetation indices and elaborated fruit weight estimation method are useful to optimize the harvest time and relating postharvest technology.
4. Digital terrain model provides the identification of micro-watersheds and evaluation of runoff and accumulation conditions, which can help to decrease the problems of surplus water and drought in the field.

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7. PUBLICATION RELATED TO THE DISSERTATION

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List of publications related to the dissertation

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