# MODELING REFLECTANCE OF URBAN CHESTNUT TREES: A SENSITIVITY ANALYSIS OF MODEL INVERSION FOR SINGLE TREES

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**ABSTRACT:**

Trees in urban environments have important ecological functions, but often suffer from suboptimal environmental conditions. Chestnut (Aesculus hippocastanum) is one of the main tree species in Germany's capital Berlin, constituting 5% of all urban trees. Recently, chestnut trees are exposed to amplified stress levels due to the horse chestnut leaf miner (Cameraria ohridella), a parasitic insect whose larvae feed exclusively on chestnut leafs. Detecting plant damages at early stages and monitoring chestnut tree stress levels are thus important to manage urban canopies in Berlin and elsewhere. Hyperspectral data offer unique opportunities to derive detailed vegetation parameters for wide areas. Vitality parameters are commonly based on the characterization of plant physiology attributes and several studies point out the usefulness of radiative transfer modeling in this context, particularly for locally heterogeneous objects such as tree canopies. However, the selection of pixels that fully represent a single tree is not easy, because the model is highly sensitive to mixed pixels or varying illumination conditions. This is challenging, because the average chestnut crown diameter is only 15m and HyMap images offer at best a ground sampling distance of 4m, resulting in a low number of pure pixels. Tree geometry introduces further disturbance through diverse illumination constellations.

In this research, we use a combination of the radiative transfer models PROSPECT and SAIL to derive parameters of chestnut tree stress levels for the city of Berlin based on HyMap images. Our goal was to quantify the influence of pixel selection methods on the quality of the model output. Reference data was collected for 11 trees and included leaf area index, leaf chlorophyll-, water- and, dry matter content. Different methods and statistical approaches to select input pixels for the modeling were compared based on several statistical parameters. Our results clearly highlight that choosing the optimum selection method is a crucial step in the model parameterization, and different selection methods lead to significantly different model results. In our case, using an averaged signal of the illuminated crown areas results in the best agreement between the model output and reference data.

## 1. INTRODUCTION

Trees perform a series of functions in urban environments, for example in urban climate, as aesthetical components in urban planning, as a living space for urban fauna, or in the context of leisure and recreation. Only a few of these functions are financially quantifiable, but urban trees are assessed as being highly valuable (Dywer et al., 1992; Konijnendijk et al., 2005; McPerson, 1992). At the same time, environmental conditions are far from natural, with sealed surfaces, high toxin levels, or high pressure of utilization (Konijnendijk et al., 2005). The necessary conservation of tree specific value and function is economically determined. Tree monitoring is hence an essential step to effectively manage urban trees. However, various factors hinder an efficient, spatially explicit, and objective survey. These include crown access or aspects of time and costs.

Hyperspectral data offer unique opportunities to derive detailed vegetation parameters for wide areas. Vitality parameters are commonly based on the characterization of plant physiological attributes. Several studies point out the flexibility of approaches based on the inversion of radiative transfer models to predict plant physiological attributes to analyze heterogeneous broadleaved canopies (Meroni et al., 2004; Zarco-Tejada, et al., 2001; Zarco-Tejada et al., 2004). In these studies, the coupled radiative transfer models (RTMs) PROSPECT (Jacquemoud et al., 1990) and SAIL (Verhoef, 1984) were used. The applicability of these models is shown, whereas some canopy specific effects constrained the accuracy, particularly the influence of shadow and crown geometry.

This research is focused on analyzing chestnut (Aesculus hippocastanum), which is one of the main tree species in Germany's capital Berlin, with hyperspectral remote sensing. Recently, chestnut trees are exposed to amplified stress levels due to the horse chestnut leaf miner (Cameraria ohridella), a parasitic insect whose larvae feed exclusively on chestnut leafs (Raimondo et al., 2003; Saello et al., 2003; Thalmann et al., 2003). Data from the Hyperspectral Mapper (HyMap) with a spatial resolution of 4m were used. However, the relation between sensor resolution and crown diameter leads to the question: Are the base assumptions behind the coupling of PROSPECT and SAIL also valid to derive vitality parameters of urban chestnut trees?

To provide information about the applicability, tree specific effects have to be considered. The crown geometry and sensor view led to complex crown shadow. Moreover, trees are represented by pure and mixed pixels, corresponding to a huge range of estimated parameters. Accordingly, four aspects will be analyzed in detail:

- Which parameters are relevant to simulate the reflectance of chestnut tree crowns?
- Single trees are represented by many pixels – which pixels contain the information to predict valid parameters?
- Is it possible to compensate the influence of the complex crown shadow?

- Are PROSPECT and SAIL adequate RTMs to estimate vitality parameters of single chestnut trees?

## 2. DATA

The choice of sample trees in urban environments is important to measure a realistic spectrum of potential canopy variations. Site specific factors, such as incoming radiance, water and nutrient availability, or pressure of use, result in a high spatial variability of canopy parameters. The phenological change within a seasonal cycle leads to additional variability and different parts of the tree crown also exhibit variations in biochemical parameters. This is mainly due to amount of light, wind pressure, or temporarily pathogenic infestations on branches. The logistic and technical constraints, such as accessible tree height, required minimum crown diameter and standardized time of data acquisition also need to be included in the tree selection process.

### 2.1 Canopy structure and biochemistry

With regard to the aforementioned criteria, eleven trees were selected. The trees were chosen from highly frequented street within built up areas (2 trees), areas next to water (3 trees), inside an urban forest (3 trees), and in a derelict military site (3 trees). To acquire a high temporal resolution of parameter change, the trees were sampled every 2 weeks from May 10$^{th}$ until September 27$^{th}$ in 2005. Individual trees were always sampled at a similar time of the day (Damm et al., 2006). LAI, crown geometry and the understorey were measured and described in terms of canopy structure. A LiCor-LAI2000 was used to measure LAI. The measurements were taken in four directions using a 180° cap and finally averaged for one tree.

Ten leafs per tree were randomly sampled from the South-facing upper crown with the aid of a cherry-picker. The harvested leafs were photographed and prepared for laboratory analysis, and spectral measurements. For the laboratory analysis, samples of a defined area (2.83cm²) were cut from the leafs and immediately placed in liquid nitrogen.

Reflectance measurements of the leafs were performed using an ASD Field Spec Pro II spectroradiometer. All measurements were taken under laboratory conditions within a van. The samples were arranged on a black background, the geometry of sensor and illumination was standardized using an ASD High Intensity Contact Probe. One measurement was performed on each leaf. The ten leaf signatures per tree were subsequently averaged for each observation date. A smooth and step filter were used to reduce remaining measurement inaccuracies and noise.

The frozen leaf samples were subsequently analyzed in the laboratory. To measure the leaf chlorophyll content, samples were crushed in acetone (85%) and loaded into a High Performance Liquid Chromatography (HPLC). Samples were weighed to derive the fresh leaf mass. To measure the dry leaf mass, samples were dried in an oven at 85°C until the mass became constant and weighed again. The water content was calculated as the difference between the fresh and dry leaf mass.

| parameter | unit | min – max (full veg. period) | min – max June 15$^{th}$ |
|---|---|---|---|
| Chlorophyll content | µg/cm² | 40 – 80 | 52 – 80 |
| Water content | g/cm² | 0.008 – 0.016 | 0.010 – 0.013 |
| Dry matter content | g/cm² | 0.004 – 0.012 | 0.008 – 0.012 |
| Mesophyll structure | unitless | 1.3 – 2.1 | 1.6 – 1.8 |
| Leaf area index | unitless | 4 – 11 | 4 – 11 |

Table 1. Field observations of canopy variables

### 2.2 Imaging spectrometer data

In this study, hyperspectral HyMap data were used. The imagery was acquired on June 20$^{th}$ in 2005, around 12 a.m. local time, i.e. five days after one of the field observation days (compare table 1). Six flight lines were acquired during a time slot of approximately one hour (solar zenith and azimuth angles between 29.8° and 35.1°; and 136.1° and 164.1°, respectively; flight headings parallel and orthogonal to the solar plane). The flight height was approximately 2000m leading to a spatial resolution of 4m. The images were geo- and radiometrically pre-processed with the modules PARGE and ATCOR4 to obtain geocoded top-of-canopy reflectance (Richter et al., 2002, Schläpfer et al., 2002).

## 3. RADIATIVE TRANSFER MODELING FOR VITALITY PARAMETER ESTIMATION

It is common to combine models calculating the reflectance of green leafs and models which combine various canopy components, like subsurface, trunk, branches or leafs (Liang, 2004). PROSPECT and SAIL are well documented and often used models to simulate reflectance and transmittance for broadleaved vegetation canopies in the spectral range of 400 to 2500 nm. PROSPECT is a leaf reflectance model and based on the plate model, developed by Allen (1969). The model treats a leaf as a pile of plates with specific attributes. Reflectance and transmittance are simulated as functions of the structural parameter (N) and the combined absorption coefficients of the leaf biochemical's chlorophyll (CAB), water (CW) and dry matter (CDM) (Jacquemoud et al., 1990). SAIL is a one-dimensional, bidirectional, turbid medium radiative transfer model, that simulates the reflectance and transmittance of vegetation canopies (Verhoef, 1984). SAIL simulates the top-of-canopy-reflectance considering various parameters: sun-sensor-geometry, fraction of diffuse radiance, canopy background, LAI, and leaf angle distribution. In this study, we used a 2M-SAIL version, suitable for dealing with an unlimited number of spectral bands and multiple canopy components (Verhoef, 1985). In the direct mode, the coupled use of PROSPECT and SAIL simulates spectral reflectance and transmittance for a certain set of canopy parameters. To retrieve canopy parameters from a measured signal, it is necessary to use the coupled models in inverse mode.

### 3.1 Experiment setting

The influence of tree specific aspects on the model accuracy was quantified, specifically:

- parameters which significantly influence the reflectance in the near infrared (NIR) and shortwave infrared (SWIR) wavelength regions
- understorey canopy
- existence of several representative pixels
- illumination conditions

The absolute RMSE between measured and estimated parameters was hence calculated for CAB and CW.

**Parameters which significantly influence the reflectance in the NIR and SWIR:** When modeling the canopy reflectance of chestnut trees using the coupled models PROSPECT and SAIL, few parameters significantly influence the reflectance in the NIR and SWIR spectral domain. To avoid the ill-posed effect, some of these parameters have to be fixed. Previous analyses at leaf level show that the structural parameter N is rather stable for chestnut trees. Furthermore, the dry matter content is relatively high, so that the signals reach saturation. According to that, the parameters N and CDM were fixed (Damm et al., 2006).
Two experiments (termed "A" and "B") were initiated to quantify the influence of LAI and CW. During experiment A, the LAI was fixed and the water content was set as free parameter. Both parameters were varied in experiment B.
**Understorey:** Analyzing the LAI, high values between 6 and 12 were observed. Canopy reflectance saturates, when the LAI exceeds values of 5 or 6 (Guyot, 1990). Accordingly, the negligibility of understorey is assumed. Both aforementioned experiments were subdivided again: In experiment A1 and B1, a frequently occurring grass spectrum was used as understorey spectrum. In the experiments A2 and B2, the understorey was changed using locally existing spectral signatures.
**Existence of several representative pixels:** First tests have shown a high variability of estimated parameters using all pixels representing one tree. This is mainly due to the tree inherent variability or mixed pixels along the crown edges. Two possibilities were analyzed to compensate this effect. First, a mean (µ1) and median (m1) spectrum for all pixels of one tree was calculated and subsequently used to estimate model parameters. Second, the mean (µ2) and median (m2) for parameter estimates from single pixels was calculated. The four calculation methods for 4 experiments lead to 16 test configurations, overall.
**Shadow:** The different crown shapes and viewing angles lead to complex illumination conditions. These conditions are expressed in a wide range of albedo values. Neglecting this effect results in significant inaccuracies (Zarco-Tejada et al., 2001). The brightness was categorized into 10 levels to evaluate which pixels have to be excluded for maintaining the model assumptions. These levels were tested in the 16 experiments.

### 3.2 Model simulation and inversion

Inversion strategies can be categorized in methods to optimize a cost function (numerical, look-up-tables (LUT)), or methods to empirically define a transfer function (e.g. artificial neuronal nets (ANN)). Different authors compared these approaches and point out advantages and constraints (Combal et al., 2002; Weiss et al., 2000). LUT-based approaches are favored to invert our model. These are simple to implement, and the results can be considered as stable, if no more then two parameters have to be inverted.
The ranges of relevant model parameters were extracted from field observations to simulate reflectance spectra (compare tables 1 and 2). N was derived using an empirical relationship with the specific leaf area, as suggested by Jaquemoud (1990). The model was adjusted to the spectral resolution of HyMap. 100.000 spectra based on parameters from Monte Carlo simulations were used to generate the LUT (table 2).

| parameter | | unit | range |
|---|---|---|---|
| N | structure parameter | - | 1.8 |
| CAB | foliage chlorophyll content | µg/cm² | 20 – 90 |
| CW | foliage water content | g/cm² | 0.008 – 0.022 |
| CDM | foliage dry matter content | g/cm² | 0.01 |
| US | understorey | - | vegetation/ soil/asphalt/ concrete/water |
| LAI | leaf area index | - | 2 – 8 |
| fW | fraction woody material | % | 0 |
| LAD | Leaf angle distribution | - | planophil |

Table 2. Ranges for Monte Carlo simulations

In order to invert PROSPECT and SAIL, we minimized the following cost function (equation 1).

$$RMSE_{rel} = \sqrt{\frac{1}{nb} * \sum_{i=1}^{nb} \left( \frac{\rho_i - \hat{\rho}_i}{\rho_i} \right)^2} \quad (1)$$

where
RMSE $_{rel}$ = relative root mean squared error
nb = number of bands
$\rho_i$ = measured reflectance of band i
$\hat{\rho}_i$ = simulated reflectance of band i

## 4. RESULTS AND DISCUSSION

The results from the 160 experiments representing different model constellations and pixel extraction methods exhibit the high variability of model outputs (fig. 1). The absolute RMSE varied between 6.7 and 20.8 for chlorophyll and between 0.0020 and 0.0073 for water content. There are no significant differences between the three experiments A1-B1, whereas experiment B2 slightly decreases in accuracy. Accuracy seems to degrade when dark or bright pixels were used for parameter estimation, which is a violation of model assumptions. Using the mean values from estimated parameters from all pixels of one tree perform generally better as parameter estimates from averaged crown spectra. If calculating these averaged crown spectra, the conflict of dark and bright pixels with the model assumptions shifts to the mean crown spectra. Calculating the mean of the estimated parameters compensates this conflict. Similar accuracies for both mean calculation methods by moderate Albedo (40%-45%) support this conclusion. Median related estimates are less accurate.

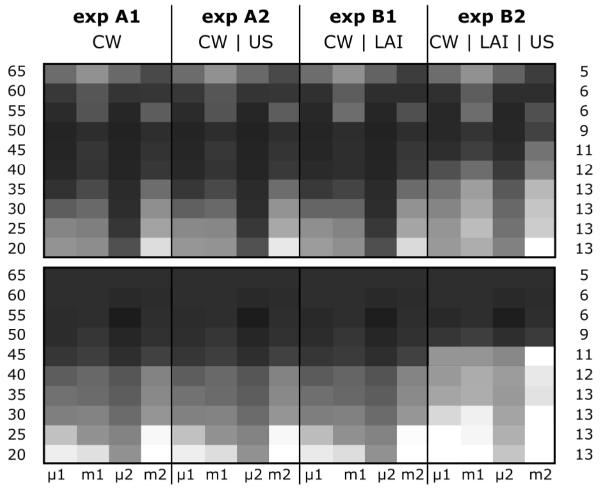


Figure 1. Accuracy matrix (RMSE absolute): chlorophyll (top) water (bottom); µ1, m1: mean and median of averaged spectra; µ2, m2: mean and median of estimates from single pixel inversion; left scale: NIR-plateau reflectance in %; right scale: n (unitless); dark colors correspond to low RMSE values, bright colors correspond to high RMSE values

The behavior of the absolute RMSE for experiments A1µ2-B2µ2 is presented in figures 2 and 3. The accuracies for experiments A1µ2, A2µ2 and B1µ2 are nearly the same. For experiment B2µ2 an overall decrease of accuracy occurs. The error for all experiments increased when the parameter estimation was based on dark or bright pixels. The canopy 3D structure and the related complex viewing and illumination conditions are not foreseen in the models.

To understand the meaning of the absolute RMSE, figure 4 and 5 present the best parameter estimates for chlorophyll and water content. To select the best model, the number of variable model parameters and the absolute RMSE should be minimized. Finally, the estimates from experiment A1µ2 with a brightness level of 45% were chosen. Comparisons between estimated and measured parameters exhibit a good one-to-one relationship between ground-truth and estimates.

To evaluate the impact of tree specific effects or general canopy aspects on the model accuracy, we examined the results of experiments A1µ2-B2µ2 in detail.

**Parameters influencing NIR and SWIR reflectance:** No significant differences occurred in the NIR and SWIR spectral domain for most of the model constellations. Only the model B2µ2 which varied the leaf area index, the water content and the understorey is a negative exception. Some parameters are available to simulate the canopy reflectance in the NIR and SWIR spectral domain, but for chestnut trees only the water content is a free parameter: The structural parameter N is less variable, the values of dry mater content and LAI saturate and must be fixed.

**Understorey:** No significant improvement was achieved by integrating variable US when the LAI was fixed (difference of averaged relative RMSE for exp A1µ2 and exp A2µ2 for CAB 0.04%; for CW 0.003%). With variable LAI and fixed US, the results are similar to the both aforementioned setups (A1µ2 and A2µ2). If LAI and US were set as free parameters, a decrease of accuracy occurred, mainly resulting from the ill-posed effect. LAI was generally underestimated (values around 2), while these low values were compensated by an overestimated water content. As the LAI with measured values of 6 to 12 has no influence on the spectral response, it should be fixed.

**Existence of several representative pixels:** A high variability of results was detected for different pixels of one tree (figures 4 and 5). This is due to the model violation when introducing extremely dark or bright pixels. However, observed average values appear very reasonable. Best result was attained by calculating the mean of the estimated parameters from single pixels (averaged relative RMSE for CAB 14% vs. 16 to 20% for other methods; relative RMSE for CW 34% vs. 38 to 41% for other methods).

**Shadow:** Best results were attained by excluding very dark and bright pixels. This is mainly caused by the crown specific geometry and the sun-view conditions, which are not foreseen in the models.

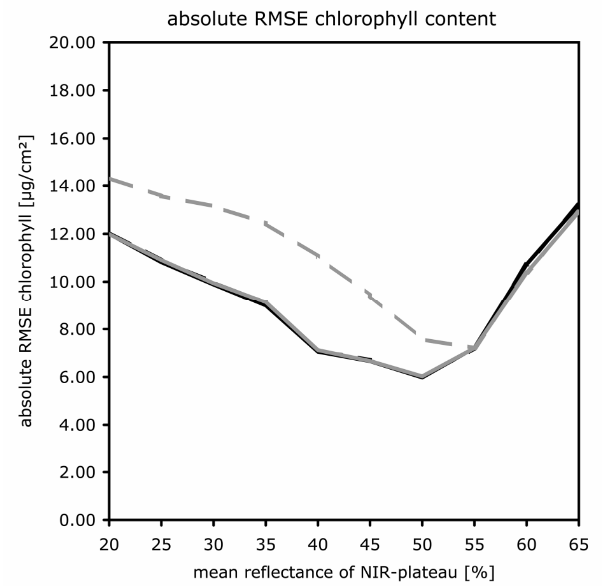


Figure 2. Absolute RMSE for chlorophyll content estimates from averaged pixel values of single trees; grey solid (exp A1); grey dashed (exp A2); black solid (exp B1), black dashed (exp B2)

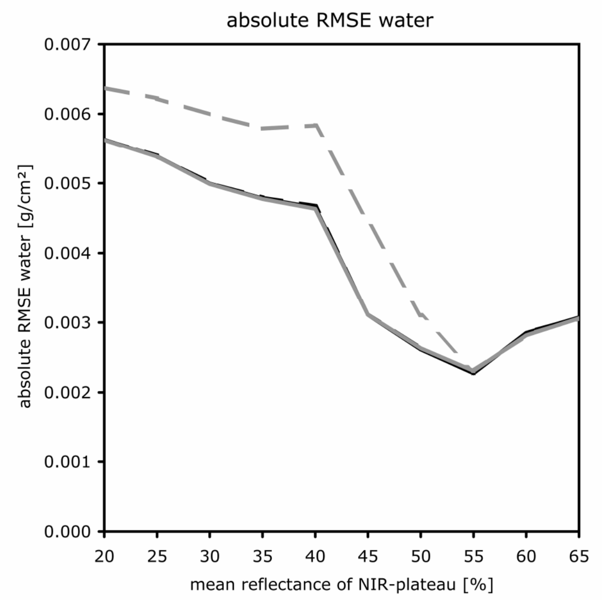


Figure 3. Absolute RMSE for water content estimates from averaged pixel values of single trees; grey solid (exp A1); grey dashed (exp A2); black solid (exp B1), black dashed (exp B2)

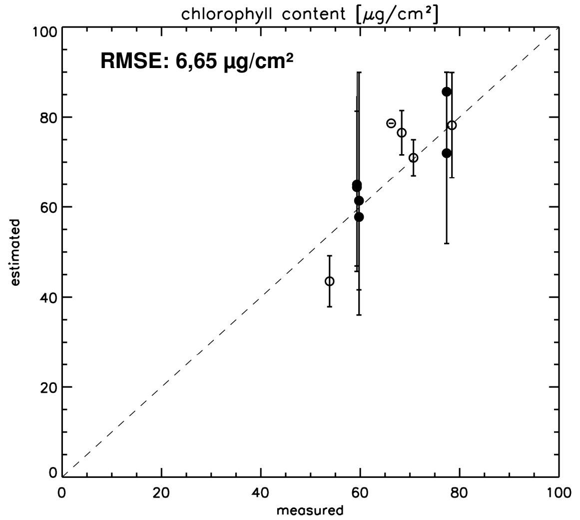


Figure 4. CAB estimates for 13 chestnut trees for best model constellation; filled circles flag trees which were mapped in two HyMap flight lines; error bars represent the range of estimated parameters

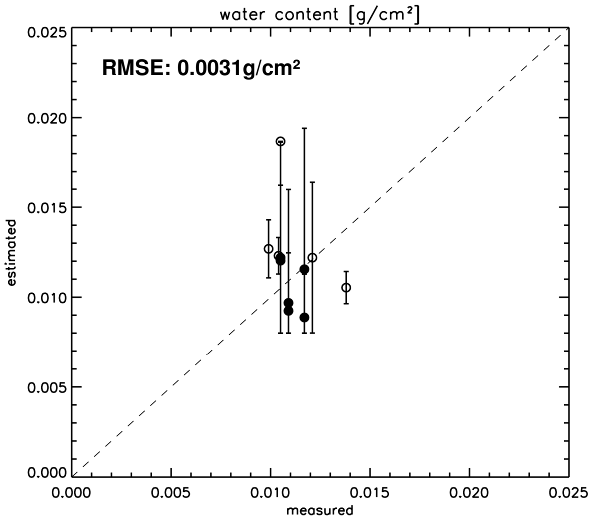


Figure 5. CW estimates for 13 chestnut trees for best model constellation; filled circles flag trees which were mapped in two HyMap flight lines; error bars represent the range of estimated parameters

## 5. CONCLUSIONS

This study aimed to determine the validity of PROSPECT and SAIL to simulate reflectance of chestnut trees. Precise and comprehensive leaf and canopy parameterization of the used models enabled a comparison of estimated and measured biochemical and structural parameters.

As anticipated, the high LAI values lead to a minor influence of understorey variations. Enhanced model accuracy is hence attainable by fixing the LAI and varying the CAB and CW parameters. For an adequate integration of several reflectance values in HyMap pixels from a single tree, calculating the mean to invert a model exhibits the best results. The influence of illumination differences induced by crown geometry can be partially compensated when excluding dark pixels. A description of the canopy's 3D structure would be essential comprehensively model this effect.

Finally, it can be stated that the combined radiative transfer models PROSPECT and SAIL offer an opportunity to estimate the vitality parameters chlorophyll and water content of chestnut trees with adequate accuracy: If pixels from the top crown are used, which are largely free of influences from the crown geometry, CAB and CW values are reliably estimated.


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## REFERENCES


**References from Journals**:

Combal, B., Baret, F., Weiss, M., Trubuli, A., Macé, D., Pragnère, A., Myeni, R., Knyazikhin, Y. & Wang, L., 2002. Retrival of canopy biophysical variables from bidirectional reflectance using prior information to solve the ill-posed inverse problem. *Remote Sensing of Environment*, 84, pp. 1-15.

Dwyer, J.F., McPherson, E.G., Schroeder, W.A. & Rowntree, R.A., 1992. Assessing the Benefits and Costs of the Urban Forest. *Journal of Arboriculture*, 18(5), pp. 227-234.

Jacquemoud, S. & Baret, F., 1990. PROSPECT: A model of leaf optical properties spectra. *Remote Sensing of Environment*, 34, pp. 75-91.

McPherson, E.G., 1992. Monitoring Urban Forest Health. *Environmental Monitoring and Assessment*, 26, pp. 165-174.

Meroni, M., Colombo, R. & Panigada, C., 2004. Inversion of a radiative transfer model with hyperspectral observations for LAI mapping in poplar plantations. *Remote Sensing of Environment*, 92, pp. 195-206.

Raimondo, F., Ghirardelli, S., & Nardini, A. & Saello, S, 2003. Impact of the leaf miner Cameraria ohridella on photosynthesis, water relations and hydraulics of Aesculus hippocastanum leafs. *Trees* 17, pp. 376-382

Richter, R. & Schläpfer, D., 2002. Geo-atmospheric processing of airborne imaging spectrometry data: Part 2. Atmospheric/topographic correction. *International Journal of Remote Sensing*, 23(13), pp. 2631-2649.

Saello, S., Nardini, A., Raimondo, F., Assunta Lo Gullo, M., Pace, F. & Giacomich, P., 2003. Effects of defoliation caused by the leaf miner Cameraria ohridella on wood production and efficiency in Aesculus hippocastanum growing in north-eastern Italy. *Trees* 17, pp. 367-375.

Schläpfer, D. & Richter, R., 2002. Geo-atmospheric processing of airborne imaging spectrometry data: Part 1. Parametric orthorectification. *International Journal of Remote Sensing*, 23(13), pp. 2609-2630.

Thalmann, C., Freise, J., Heitland, W. & Bacher, S., 2003. Effects of defoliation by horse chestnut leafminer ( Cameraria ohridella) on reproduction in Aesculus hippocastanum. *Trees*, 17, pp. 383-388.

Verhoef, W., 1984. Light scattering by leaf layers with application to canopy reflectance modelling: The SAIL model. *Remote Sensing of Environment*, 16, pp. 125-141.

Verhoef, W., 1985. Earth observation modelling based on layer scattering matrices. *Remote Sensing of Environment*, 17, pp. 165-178.

Weiss, M., Baret, F., Ranga, M.B., Pragnère, A. & Knazikhin, Y., 2000. Investigation of a model inversion technique to estimate canopy biophysical variables from spectral and directional reflectance data. *Agronomy*, 20, pp. 3-22.

Zarco-Tejada, P.J., Miller, J.R., Noland, T.L., Mohammed, G.H. & Sampson, P.H., 2001. Scaling-up and model inversion methods with narrowband optical indices for chlorophyll content estimation in closed forest canopies with hyperspectral data. *IEEE Transactions on Geoscience and Remote Sensing*, 39(7), pp. 1491-1507.

Zarco-Tejada, P.J., Miller, J.R., Morales, A., Berjon, A. & Agüera, J., 2004. Hyperspectral indices and model simulation for chlorophyll estimation in open-canopy tree crops. *Remote Sensing of Environment*, 90, pp. 463-476.

**References from Books**:
Konijnendijk C.C., Nilsson, K., Randrup, T.B. & Schipperijn, J., 2005. *Urban Forest and Trees*. Springer 520 pp.

Liang, S., 2004. *Quantitative remote sensing for land surface characterisation*. Wiley 534 pp.

**References from Other Literature**:
Damm, A. & Hostert, P., 2006. Deriving vitality parameters of Aesculus hippocastanum using radiative transfer models. *1st Workshop of the EARSeL Special Intrest Group Urban Remote Sensing "Challenges and Solutions"*. Berlin, Germany.

Guyot, G., 1990. Optical properties of vegetation canopies. *Steven & Clark (Ed.): Applications of remote sensing in agriculture*. Butterworth, London, pp. 19-43.