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DOLOČANJE INDEKSA LISTNE POVRŠINE LISTNATEGA GOZDA NA POVODJU DRAGONJE – 1. DEL: METODE IN MERITVE
ESTIMATING LEAF AREA INDEX OF THE DECIDUOUS FOREST IN THE DRAGONJA WATERSHED – PART I: METHODS AND MEASURING

Mojca ŠRAJ

V raziskovalni študiji so bile narejene natančne meritve in analize posameznih komponent hidrološkega kroga gozda in parametrov vegetacije s sodobno mersko opremo na eksperimentalnem povodju Dragonje. V ta namen sta bili v sodelovanju z univerzo Vrije Universiteit iz Amsterdama konec leta 1999 v listnatem gozdu na povodju Dragonje izbrani dve merski ploskvi, ena na severnem (1419 m^2) in druga na južnem pobočju hriba (615 m^2) nad sotočjem Dragonje in Rokave. Gozda na severni in južni strani se opazno razlikujeta, tako v strukturi, gostoti in velikosti dreves kot v sami sestavi. Na obeh ploskvah so bile natančno določene lastnosti vegetacije. Na severni strani skoraj polovico dreves predstavlja kraški gaber (Carpinus orientalis croaticus) (47%), sledi pa mu hrast puhovec (Quercus pubescentis) (34%). Na tej strani najdemo še jesen (Fraxinus ornus, javor (Sorbus torminolis) in rumeni dren (Cornus Mas). Na južni strani več kot polovico dreves predstavlja jesen (54%), sledi pa mu hrast puhovec (26%). Na tem pobočju so v manjši meri zastopani še kraški gaber, javor in rumeni dren. Meritve so se začele jeseni 2000. Indeks listne površine LAI se je določal po treh metodah: neposredni metodi zbiranja odpadlega listja, metodi hemisferičnega fotografiranja in metodi merjenja fotosintetskega aktivnega sevanja (PAR). Na vsaki ploskvi posebej so se v desetih posebnih košarah redno zbirale količine odpadlega listja, v istih točkah se je izvajalo tudi hemisferično fotografiranje krošenj in 3 serije meritev fotosintetskega aktivnega sevanja PAR. Za potrebe določanja indeksa listne površine je bila najpogostejšim vrstam dreves določena specifična površina listov SLA.
Ključne besede: *indeks listne površine (LAI), specifična listna površina (SLA), gozdna hidrologija, Dragonja*

In the research study detailed measurements and analyses of components of the forest hydrological cycle and vegetational parameters were performed, using up-to-date measuring equipment on the experimental Dragonja watershed. Within the research project carried out in co-operation with the Vrije Universiteit, Amsterdam, two plots were selected at the end of 1999 in the deciduous forest of the Dragonja watershed, one on the north-facing slope (1419 m^2) and the other on the south-facing slope (615 m^2) on the hill above the confluence of the Dragonja River and Rokava River. There are considerable differences between the forests on the northern and southern slopes, i.e. in terms of structure, density, tree height and composition. On both plots the characteristics of vegetation were specified in detail. On the north plot almost half of the trees are hornbeam trees (Carpinus orientalis croaticus) (47%), followed by pubescent oak (Quercus pubescentis) (34%). The forest also includes ash (Fraxinus ornus), maple (Sorbus torminolis) and cornelian cherry dogwood (Cornus Mas). On the south plot more than half of the trees are represented by ash (54%), followed by pubescent oak (26%). On the plot hornbeam, maple and cornelian cherry dogwood are also found. The measurements started in autumn 2000. Leaf area index (LAI) was estimated with three methods: direct litterfall collection method, method of hemispherical photography, and method of photosynthetically active radiation (PAR). On each plot, litterfall was collected in 10 baskets, and at the same points the hemispherical photography of canopy and 3 sets of PAR measurements were performed. For establishing the LAI index the specific leaf area was established for the most frequent trees.
Key words: *leaf area index (LAI), specific leaf area (SLA), forest hydrology, Dragonja*

1. UVOD

Hidrologija je veda, ki preučuje kroženje vode v naravi, njene pojavne oblike, razporeditev na zemlji, njeno gibanje ter fizikalne in kemične lastnosti (Chow, 1964). Ukvarja se predvsem s kroženjem vode na kopnem, torej z izmenjavo vode med atmosfero, površino zemlje in vodnimi sistemi na njej (Brilly in Šraj, 2000).

Gozdna hidrologija preučuje kroženje vode na z gozdom poraščenih površinah. Preučuje poti in načine prehajanja vode iz atmosfere skozi gozdni ekosistem v tla, podtalnico in površinske vode ter vračanje vode nazaj v ozračje (Smolej, 1988).

Padavine so glavni vir vode hidrološkega kroga v gozdu (slika 1). Večinoma predstavljata padavine dež ali sneg, v obmorskih in goratih gozdnih predelih pa se pojavljajo tudi horizontalne padavine – megla. Ponavadi velik del padavin, padlih nad gozdom, prestrežejo drevesne krošnje, manjši del pa jih pade skozi odprtine med krošnjami in listi naravnost na tla – prepuščene padavine. Količina prestreženih padavin (Mikoš *et al.*, 2002) je odvisna od vegetacijskih in meteoroloških parametrov:

1. Kapacitete krošnje, le-ta pa je odvisna od vrste, velikosti, oblike in starosti vegetacije, površine in orientacije listov (iglaste vrste dreves prestrezajo 20–40 %, listnate pa 20–25 % padavin, z večjo starostjo vegetacije delež prestreženih padavin narašča (Geiger *et al.*, 1995)).
2. Gostote vegetacije (z gostoto dreves prestrežene padavine naraščajo).
3. Intenzitete, trajanja in pogostosti padavin (manjša intenziteta ali kratko trajanje omogočata večje izhlapevanje s krošenj, intenziteta izhlapevanja je največja na začetku nevihte, pogostejše padavine zmanjšujejo prestrežene padavine).
4. Vrste padavin (pri iglastih vrstah dreves vodni ekvivalent prestreženih snežnih padavin presega količino prestreženih tekočih padavin).
5. Klimatskih pogojev (višja temperatura omogoča večje izhlapevanje, veter lahko znatno vpliva na izhlapevanje).

1. INTRODUCTION

The hydrological science studies the circulation of water in the nature, its phenomena, distribution on the earth, movement and physico-chemical characteristics (Chow, 1964). It mainly deals with circulation of water between the atmosphere, surface of the earth and its water systems (Brilly and Šraj, 2000).

Forest hydrology studies the circulation of water in forested areas. It studies the course and ways of transition of water from the atmosphere through the forest ecosystem into the ground, groundwater and surface waters and its return back to the atmosphere (Smolej, 1988).

Precipitation is the main source of water in the hydrological circle (Figure 1). Mostly it is represented by rain and snow, however, in the coastline and in mountainous, forested areas horizontal precipitation occurs, i.e. fog. Usually, most of the precipitation above the forest is intercepted by canopy, and a smaller part falls through the gaps between canopy and leaves to the ground – throughfall. Intercepted precipitation (Mikoš *et al.*, 2002) depends on vegetational and meteorological parameters:

1. Canopy capacity, which depends upon the class of species, size, shape and vegetational age, area and leaf orientation (coniferous trees intercept 20–40 %, and decidous trees 20–25 % precipitation; the higher the vegetational age, the higher the intercepted precipitation (Geiger *et al.*, 1995)).
2. Vegetational density (interception increases with tree density).
3. Intensity, duration and frequency of precipitation (smaller intensity or short duration result in higher evaporation rate from canopy, intensity of evaporation rate is highest at the beginning of storms, frequently occurring precipitation reduces interception).
4. Precipitation type (with coniferous species the water equivalent of intercepted snow exceeds the value of intercepted liquid precipitation).
5. Climate conditions (higher temperatures cause higher evaporation rate, the wind can have high influence over evaporation).
6. Periods in the course of the year (growing

6. Časovnega obdobja v letu (obdobje rasti, obdobje mirovanja vegetacije).

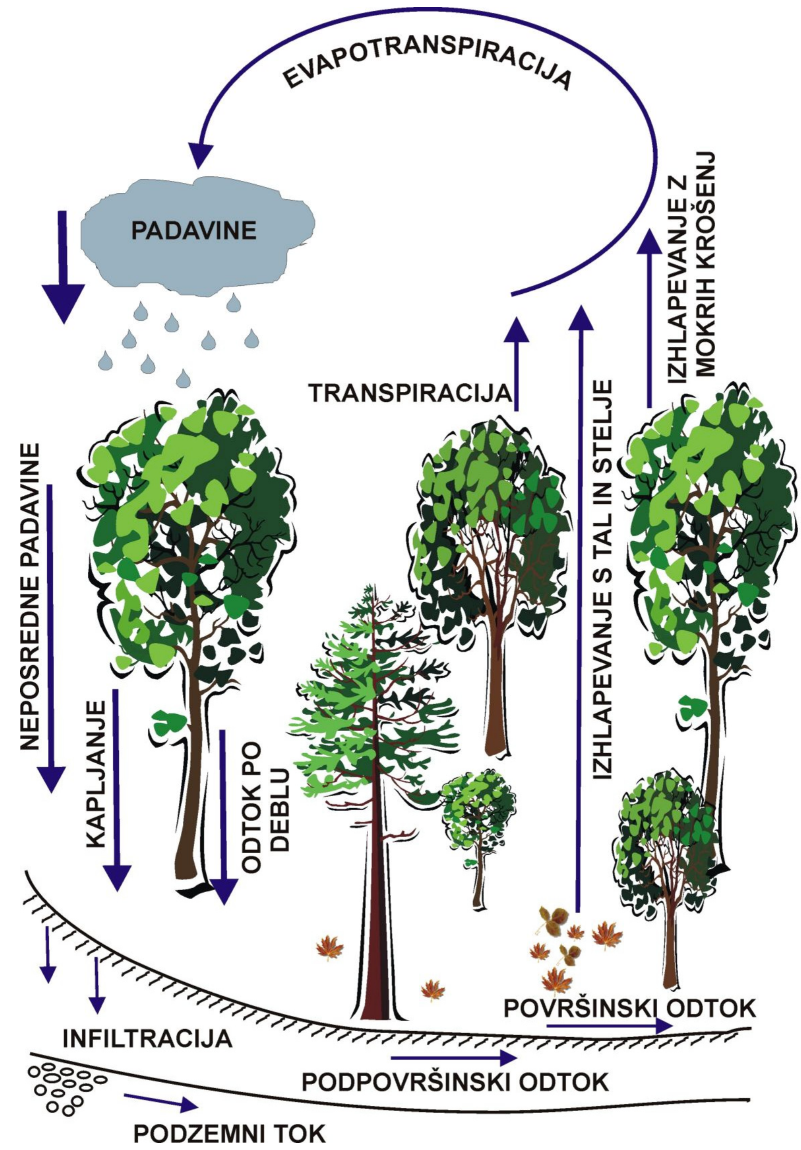
Ovington (1954) je na podlagi raziskav zaključil, da je količina prestreženih padavin lahko od 6 do 93 odstotkov oziroma da je glede na zelo različne pogoje možen zelo različen delež prestreženih padavin.

Eden pomembnejših parametrov vegetacije pri procesih, kot so prestrezanje padavin, izhlapevanje, transpiracija, evapotranspiracija in kroženje energije, je indeks listne površine.

period, dormant period).

Based upon research, Ovington (1954) concluded that the quantity of intercepted precipitation may vary between 6 and 93 percent, i.e. in different conditions a very different interception rate may be achieved.

The leaf area index is one of the most important parameters of vegetation in terms of processes, such as precipitation interception, evaporation, transpiration, evapotranspiration and energy circulation.



Slika 1. Gozdni hidrološki krog.

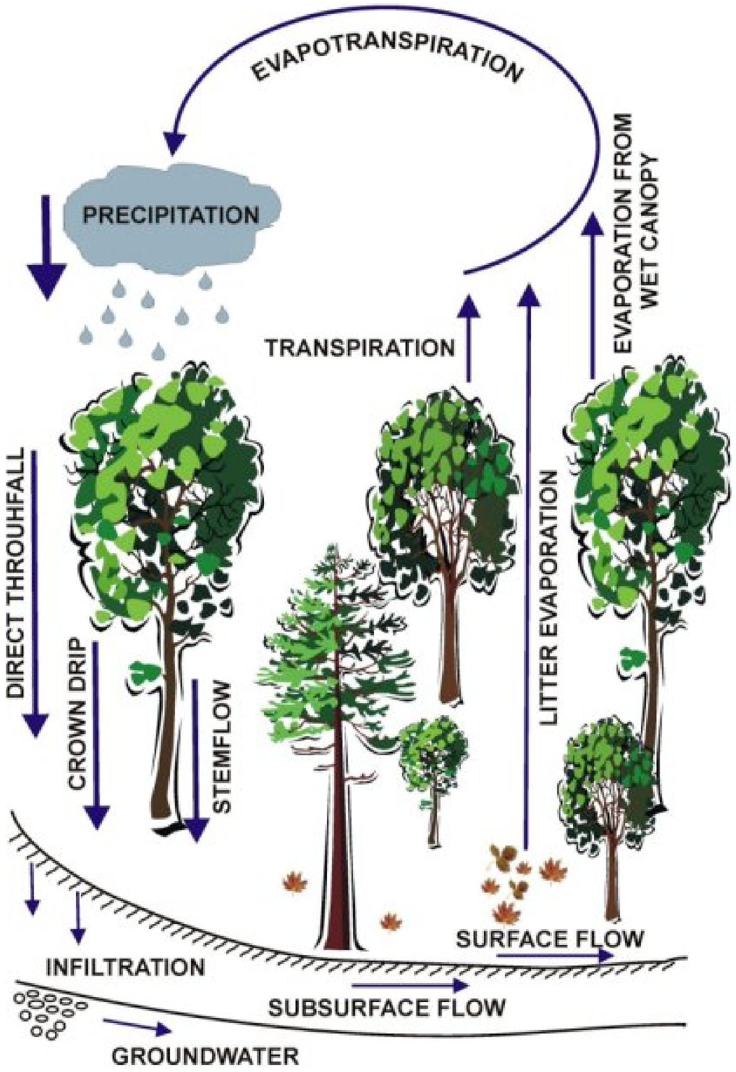


Figure 1. Forest hydrological cycle.

2. METODE DOLOČANJA INDEKSA LISTNE POVRŠINE (*LAI*)

Indeks listne površine (*LAI*, angl. orig. leaf area index) je definiran kot skupna enostranska površina zelenih listov na enoto površine tal [m^2/m^2] (Watson, 1947; Chen et al., 1997; FAO, 2002). Točnost določitve indeksa listne površine je lahko kritična pri razumevanju in modeliranju obnašanja posameznega ekosistema. Medtem ko so za posamezne vegetacije nizke rasti, kot so npr. poljedelske rastline, indeksi listne površine že zelo natančno določeni (van Dijk in Bruijnzeel, 2001b), pa ostaja določitev listnega indeksa naravnih gozdnih sestavov še vedno velik logistični problem. Za *LAI* je značilna prostorska in časovna spremenljvost, ki je v

2. METHODS FOR ESTIMATING THE LEAF AREA INDEX (*LAI*)

Leaf are index (*LAI*) is defined as the total one-sided leaf area per unit ground area [m^2/m^2] (Watson, 1947; Chen et al., 1997; FAO, 2002). Accuracy in estimating *LAI* may be critical in understanding and modelling of the behaviour of a single ecosystem. While *LAI* has been quite accurately estimated for low growing vegetation, such as agricultural plants (van Dijk in Bruijnzeel, 2001b), the estimation of leaf area index of natural forest compositions remains a big logistic problem. Characteristic of *LAI* is the spatial and time variability, which primarily depends on the type of vegetation and climate. In estimating največji meri odvisna od vrste vegetacije in podnebja. Za določanje *LAI* raziskovalci uporabljajo različne metode, ki jih v splošnem delimo na neposredne in posredne. Neposredne metode so zanesljivejše, vendar zahtevajo veliko časa in laboratorijskega dela. Posredne metode, pri katerih se indeks listne površine določi preko merjenja in analize nekih drugih parametrov, pa so hitrejše in zato omogočajo tudi zajem večjega prostorskega vzorca. Večina jih temelji na metodi določanja deleža odprtin v krošnji. Njihova pomankljivost pa je, da ne ločijo površine listov od površine vej in debla.

Neposredne metode za določanje *LAI* so:

1. Zbiranje in določanje količine odpadlega listja.
2. Sekanje rastlin in določanje celotne listne površine rastline.

Med posrednimi metodami določanja *LAI* pa so najpomembnejše:

1. Merjenje količine prehajanja sončnega sevanja skozi krošnje s posebnimi senzorji.
2. Hemisferično fotografiranje krošenj.
3. Alometrične metode.
4. Določanje *LAI* s pomočjo satelitskih posnetkov.

2.1 METODA ZBIRANJA IN DOLOČANJA KOLIČINE ODPADLEGA LISTJA

Je zelo natančna metoda, vendar zahteva ogromno časa in zamudnega laboratorijskega dela. Ponavadi se uporablja v kombinaciji z eno od posrednih metod in služi za njeno kalibracijo. Uporabljena je bila v mnogih raziskavah (Bartelink, 1998; Chason *et al.*, 1991; Clough *et al.*, 2000; Maass *et al.*, 1995; Nebel *et al.*, 2001, Šraj, 2003). Metoda je najprimernejša za listopadni gozd, ki ima omejeno obdobje odpadanja listov. Temelji na predpostavki, da v košare za zbiranje listja lovimo naključne vzorce odpadajočega listja nad njimi. Indeks listne površine se izračuna iz mase posušenih listov na enoto površine in prej dololočene specifične površine listov *SLA*.

2.2 SEKANJE RASTLIN IN DOLOČANJE CELOTNE LISTNE POVRŠINE RASTLINE

Metoda je uničevalna in iz tega razloga

LAI, researchers have used several different methods, which are generally divided into direct and indirect ones. Direct methods are more reliable, but they are time-consuming and require more laboratory work. Indirect methods, where *LAI* is established through measurements and analyses of some other parameters, are faster and thus enable the coverage of a larger spatial sample. Mostly, they are based on the method of estimating the canopy gap fraction. Their primary weakness is that they do not distinguish between leaf area and area of branches and trunks.

Indirect methods for establishing the *LAI* are:

1. Litterfall collection and estimation.
2. Destructive sampling method and estimating the entire leaf area of a plant.

Among the indirect methods of estimating *LAI*, the most prominent include:

1. Measuring the transition of solar radiation through canopy with special sensors.
2. Hemispherical photography of the canopy.
3. Allometric methods.
4. Estimating *LAI* with satellite imaging.

2.1 LITTERFALL COLLECTION METHOD

Litterfall collection method is a very accurate method, but it takes a lot of time-consuming laboratory work. It is used in combination with one of the direct methods and serves for the calibration of the other methods. It was used in numerous studies (Bartelink, 1998; Chason *et al.*, 1991; Clough *et al.*, 2000; Maass *et al.*, 1995; Nebel *et al.*, 2001, Šraj, 2003). The method is best applicable in deciduous forests, where there is a limited period of leaves falling off. It is based on assumption that random samples of leaves are collected in the baskets. The *LAI* is calculated from the mass of dried leaves over area unit and previously determined specific leaf area *SLA*.

2.2 DESTRUCTIVE SAMPLING METHOD

This is a destructive type of method and thus undesirable. It is suitable for example for nezaželena. Primernejša je recimo za poljedelske rastline (Chen *et al.*, 1997; Leuning *et al.*, 1994; Levy in Jarvis, 1999; Whitford *et al.*, 1995), za gozdove pa takorekoč neuporabna, saj je količina biomase, ki bi jo bilo treba uničiti, nedopustno velika.

2.3 MERJENJE KOLIČINE PREHAJANJA SONČNEGA SEVANJA SKOZI KROŠNJE S POSEBNIMI SENZORJI

Metoda (Chason *et al.*, 1991; Chen, 1995; Le Dantec *et al.*, 2000; Law *et al.*, 2001; Martens *et al.*; 1993; Maass *et al.*, 1995; Nilson, 1971; Kodani *et al.*, 2002; McPherson in Peper, 1998) temelji na določanju deleža odprtin v krošnji in je zasnovana na štirih predpostavkah (Li-Cor, 1990):

- listje je črno in kot tako ne odbija in ne prepušča svetlobe;
- posamezni listi so majhni;
- listje je porazdeljeno naključno;
- listje je orientirano azimutsko naključno.

Delež odprtin zavzema vrednosti med 0 (popolnoma prekrito nebo) in 1 (popolnoma odprto nebo). Seveda v naravi nobena vegetacija ne more v celoti izpolnjevati zgornjih predpostavk. Listje navadno ni razporejeno naključno, temveč je zbrano okrog vej. Lahko pa govorimo o neki naključni razporeditvi v sami krošnji. Res pa ima listje majhno prepustnost in odbojnost. Vse te ugotovitve so upoštevane pri metodi določanja *LAI* s pomočjo različnih senzorjev. Najbolj razširjen instrument iz te skupine med raziskovalci in eden novejših je LAI-2000 Plant Canopy Analyser (Li-Cor, 1990). To je optično-elektronska naprava, ki deluje na principu optičnega senzorja in simulira širokokotni objektiv "ribje oko" (angl. orig. fish-eye). Poleg širokokotne leče ima vgrajen tudi detektor sevanja. Instrument izračuna *LAI* iz meritev sevanja pod in nad krošnjami. Uporablja se lahko tudi Ceptometer, ki meri fotosintetsko aktivno sevanje (angl. orig. Photosynthetically Active Radiation ali *PAR*). *PAR* je del spektra sončnega sevanja, ki ga lahko uporabijo zelene rastline, in sicer med 380 in 710 nm valovne dolžine (Diaci, 1999). *LAI* se lahko izračuna iz razmerja med *PAR* pod krošnjami in nad krošnjami, koeficienta pojemanja svetlobe pri prehodu skozi krošnje posamezne vegetacije (κ, angl. orig. canopy

crops (Chen *et al.*, 1997; Leuning *et al.*, 1994; Levy in Jarvis, 1999; Whitford *et al.*, 1995), but practically unusable for forests, since the biomass quantity that needs to be destroyed is inadmissably large.

2.3 MEASURING THE TRANSIMISSION OF SOLAR RADIATION THROUGH FOREST CANOPY WITH SPECIAL SENSORS

The method (Chason *et al.*, 1991; Chen, 1995; Le Dantec *et al.*, 2000; Law *et al.*, 2001; Martens *et al.*; 1993; Maass *et al.*, 1995; Nilson, 1971; Kodani *et al.*, 2002; McPherson and Peper, 1998) is based on establishing canopy gap fraction, and has been based on four assumptions (Li-Cor, 1990):

- the foliage is black and thus does not reflect or transmit any light;
- the foliage elements are small;
- the foliage is randomly distributed;
- the foliage is azimuthally randomly oriented.

Canopy gap fraction is estimated from 0 (fully covered sky) to 1 (fully open sky). Notably, in nature no vegetation can ever fit into the extreme-type assumptions. The foliage is usually not random but is collected around branches. However, we can assume that there is random distribution in the canopy itself. The foliage has little transmittance or reflection. All these observations are taken into consideration in establishing *LAI* with different sensors. One of the most widely used and recently introduced instruments is LAI-2000 Plant Canopy Analyser (Li-Cor, 1990). This is an optical-electronic device functioning on the principle of an optical sensor and simulating the fish-eye wide-angle lens. Besides the wide-angle lens it has a built-in radiation dector. The instrument calculates *LAI* from measurements of radation below and above the canopy. A Ceptometer can also be used, measuring the Photosynthetically Active Radiation (*PAR)*. *PAR* is part of the solar radiation spectrum between 380 and 710 nm of wave length, which can be used by green plants (Diaci, 1999). *LAI* can be calculated between the ratio of incident and transmitted light extinction coefficient) in Beer-Lambertovega zakona (Pierce in Running, 1988). Pojemanje sončnega sevanja pri prehodu skozi vegetacijo je odvisno od razporeditve in gostote listov ter njihove prepustnosti:

PAR, canopy light extinction coefficient (κ) and the Beer-Lambert law (Pierce in Running, 1988). The canopy light extinction during transmission through vegetation depends on distribution and foliage density as well as its transmittance:

$$Q_p = Q_i \cdot e^{-\kappa \cdot LAI} \qquad (1)$$

Posamezni členi enačbe so:

- Q_p prepuščeno sončno sevanje, izmerjeno pod krošnjami [nmol/m^2/s];
- Q_i vpadlo sončno sevanje, izmerjeno nad krošnjami [nmol/m^2/s];
- κ koeficient pojemanja [-];
- LAI indeks listne površine [-].

Single elements in the equation are:

- Q_p transmitted solar radiation, measured below canopy [nmol/m^2/s];
- Q_i incoming solar radiation, measured above canopy [nmol/m^2/s];
- κ light extinction coefficent [-];
- LAI leaf area index [-].

2.4 HEMISFERIČNO FOTOGRAFIRANJE KROŠENJ

Je določanje deleža odprtin v krošnji s posebno obdelavo in analizo fotografij (Frazer *et al.*, 2001; McPherson in Peper, 1998; Walter in Torquebiau, 2000; Chen *et al.*, 1991; van Gardingen *et al.*, 1999; Levy in Jarvis, 1999; Hale in Edwards, 2002). Najpogosteje se v raziskavah uporablja posebna širokokotna leča "ribje oko" (fish-eye) z vidnim poljem 180^0, lahko pa se uporabijo tudi druge leče. Osnovni princip metode je, da nebesni svod, ki je prekrit s krošnjami dreves, projiciramo na ravno podlago. Pri fotografiranju je zelo pomembna osvetlitev, da dobimo dober kontrast med listjem in nebom. Chen s sodelavci (1991) priporoča tako nastavitev osvetlitve, da dobimo belo nebo. Dobili naj bi jo z osvetlitvijo, povečano za 1 do 2 stopnji (1+, 2+), relativno glede na avtomatsko določeno osvetlitev fotoaparata. Priporočljivo je, da slikamo ob jasnem vremenu. Izračun *LAI* iz meritev deleža odprtin preko hemisferičnih fotografij so podali mnogi avtorji, med njimi tudi Nilson (1971) ter Lang in Yueqin (1986). Delež razpršenega sevanja, ki pride skozi krošnje, – $T(\theta)$ – lahko izrazimo kot razmerje med razpršenim sevanjem pod krošnjami in nad krošnjami pri določenem kotu. $T(\theta)$ imenujemo prepuščeno sevanje ali delež odprtin v krošnji. Če so

2.4 HEMISPHERICAL PHOTOGRAPHY OF CANOPY

Hemispherical photography is a method of establishing the gap canopy fraction by way of special processing and photography analysis (Frazer *et al.*, 2001; McPherson & Peper, 1998; Walter & Torquebiau, 2000; Chen *et al.*, 1991; van Gardingen *et al.*, 1999; Levy & Jarvis, 1999; Hale & Edwards, 2002). In studies, mainly the fish-eye wide-angle lens is used with 180^0 field-of-view. The basic principle of the method is to project the sky covered with tree canopies onto a level base. The brightness is of utmost importance in photography in order to achieve good contrast between the foliage and sky. Chen *et al.* (1991) suggest such settings of brightness, so that the sky is white. It should be achieved with brightness plus 1 to 2 levels (1+, 2+), with regard to the automatic settings of brightness of the instrument. It is advisable to take pictures in clear weather conditions. Calculation of *LAI* from measuring canopy gap fraction through hemispherical photography was proposed by several authors, among others Nilson (1971) and Lang & Yueqin (1986). The diffused radiation fraction that transmits through canopy $T(\theta)$ can be expressed as the ratio between diffused radiation below canopy and above canopy at a specific angle. $T(\theta)$ is called transmitted solar radiation or canopy gap fraction. If the gaps are large and equally distributed, as with odprtine velike ali enakomerno razporejene, kot npr. pri iglastih drevesih ali pri vegetaciji, ki raste v vrsti, je prepuščeno sevanje večje kot skozi listje naravnega gozda, kjer so listi razporejeni na enaki površini naključno, zato so tudi enačbe, ki se uporabljajo za različne vrste vegetacij, drugačne. Za naravni listnati gozd je delež odprtin v krošnjah odvisen od gostote in orientacije listov ter dolžine poti skozi krošnje. S pomočjo Beer-Lambertovega zakona dobimo:

coniferous trees or with vegetation growing in a straight line, the transmitted radiation is higher than the radiation through the foliage of natural forests, where the foliage is randomly distributed, thus the equations for different types of vegetation are different. For natural deciduous forests the canopy gap fraction depends on density and orientation of the foliage as well as on the pathlength through the canopy. The Beer-Lambert Law proposes as follows:

$$T(\theta) = e^{(-G(\theta)\cdot\mu\cdot H(\theta))} \quad \text{ali/}or \quad -\ln(T(\theta)) = G(\theta)\cdot\mu\cdot H(\theta) \tag{2}$$

V enačbi (2) je:

- $T(\theta)$ delež prepuščenega sončnega sevanja ali delež odprtin v krošnji [-];
- $G(\theta)$ delež listov projeciranih v smeri kota θ [-];
- $H(\theta)$ dolžina poti skozi krošnjo za vsak kot θ [m];
- θ zenitni kot [^{0}];
- μ gostota listja [m^2/m^3].

In Equation (2):

- $T(\theta)$ is the fraction of beam penetration or gap fraction [-];
- $G(\theta)$ is the fraction of foliage projected towards angle θ [-];
- $H(\theta)$ is pathlength through the canopy for each view angle θ [m];
- θ is zenith angle [^{0}];
- μ is foliage density [m^2/m^3].

Enačbo za gostoto listja je podal Miller (1967):

Equation for foliage density was proposed by Miller (1967):

$$\mu = -2\int_0^{\pi/2} \frac{\ln(T(\theta))}{H(\theta)}\cdot \sin\theta \, d\theta \tag{3}$$

Če je $H(\theta)$ znan, lahko enačbo (3) uporabimo za katerokoli obliko krošenj. Za krošnjo višine (z) velja:

If $H(\theta)$ is known, then Equation (3) can be applied to any canopy shape. For a canopy of size (z) stands:

$$H(\theta) = \frac{z}{\cos\theta} \tag{4}$$

$$LAI = \mu\cdot z \tag{5}$$

Enačbo (5) lahko sedaj zapišemo:

Equation (5) can be expressed as:

$$LAI = -2\int_0^{\pi/2} \ln(T(\theta))\cos\theta\sin\theta \, d\theta \tag{6}$$

2.5 ALOMETRIČNE METODE

Temeljijo na določanju *LAI* preko osnovnih

2.5 ALLOMETRIC METHODS

Allometric methods are based on estimating the *LAI* through the basic physical fizikalnih lastnosti vegetacije, kot npr. premer debla na določeni višini, višina dreves, biomasa ipd. s predhodno natančno določenim odnosom med posameznimi parametri (*Chen et al.*, 1997; Jackson, 2000; Karlik in McKay, 2002; McPherson in Peper, 1998; Nowak, 1996). Ta odnos se določi na reprezentativnem manjšem vzorcu z eno od neposrednih metod.

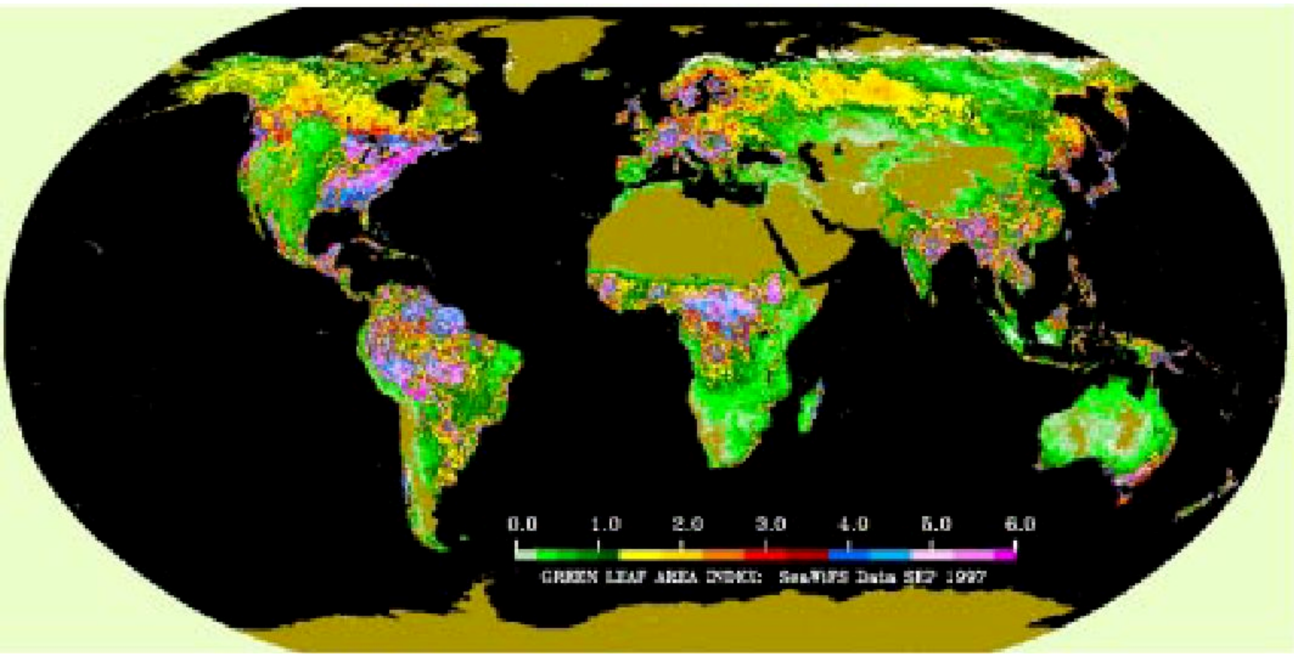
characteristics of vegetation, such as trunk diameter at certain height, tree size, biomass etc. with previously accurately determined relationship between parameters (Chen *et al.*, 1997; Jackson, 2000; Karlik & McKay, 2002; McPherson & Peper, 1998; Nowak, 1996). The relationship is established on a small representative sample with one of the direct methods.

2.6 METODA DOLOČANJA *LAI* S POMOČJO SATELITSKIH POSNETKOV

Metoda (Birky, 2001; Fassnacht *et al.*, 1997; Myneni in Running, 1999) temelji na analizi satelitskih merjenj IR svetlobe (slika 2). Z naraščanjem *LAI* odboj IR svetlobe zaradi absorbcije pada.

2.6 METHOD OF ESTIMATING *LAI* WITH SATELLITE IMAGING

The method (Birky, 2001; Fassnacht *et al.*, 1997; Myneni & Running, 1999) is based on analysis of satellite measurements of IR light (Figure 2). By increase of *LAI* the reflection of IR light decreases due to absorption.



Slika 2. Globalni *LAI*, določen s pomočjo SeaWiFs (angl. orig. sea-viewing wide field-of-view senzor) za september in oktober 1997 (Myneni in Running, 1999).
Figure 2. Global LAI estimated by SeaWiFs sea-viewing wide field-of-view sensor for September and October 1997 (Myneni & Running, 1999).

2.7 SPREMENLJIVOST *LAI*

Med posameznimi ekosistemi se indeks listne površine zelo spreminja, od manj kot 1 m^2/m^2 (aridni predeli) (Scurlock *et al.*, 2001) do več kot 10 m^2/m^2 (nekateri iglasti gozdovi) (Scurlock *et al.*, 2001; Maass *et al.*, 1995; Roberts, 2000). Določanje indeksa listne površine je tema mnogih raziskovalcev po

2.7 VARIABILITY OF *LAI*

Between ecosystems leaf area index has a high degree of variability, from less than 1 m^2/m^2 (arid land) (Scurlock *et al.*, 2001) to more than 10 m^2/m^2 (some coniferous forests) (Scurlock *et al.*, 2001; Maass *et al.*, 1995; Roberts, 2000). Estimation of *LAI* is the research topic of many researchers around the svetu (preglednica 1). Največ študij je bilo narejenih za iglaste gozdove v različnih podnebnih pogojih (Chen *et al.*, 1991; Law *et al.*, 2001; Thomas in Winner, 2000), manj pa za listnate (Chason *et al.*, 1991; Le Dantec *et al.*, 2000; McPherson in Peper, 1998) in tropske gozdove (Clough *et al.*, 2000; Maass *et al.*, 1995; Nebel *et al.*, 2001; Schellekens, 2000). Indeks listne površine se lahko zelo spreminja, tako časovno kot prostorsko. Za listnati gozd se npr. *LAI* spreminja sezonsko in je največji v rastni dobi ter najmanjši v mirujočem obdobju vegetacije (v Sloveniji pozimi). Upoštevanje časovnega spreminjanja je zelo pomembno za razumevanje dobljenih razlik pri raznih fizikalnih in bioloških procesih ekosistema (npr. izhlapevanju). Prostorska spremenljivost indeksa listne površine je predvsem posledica različnih pogojev za rast. *LAI* se spreminja tudi znotraj posameznega ekosistema, odvisno od danih pogojev. V več študijah je bila dokazana povezava med indeksom listne površine in razpoložljivimi količinami vode (Le Dantec *et al.*, 2000; Maass *et al.*, 1995). Pomanjkanje vode ne zmanjša le površine listov, temveč tudi njihovo število. Suša vpliva na površino listov neposredno z vplivom na rast in posredno na ravnotežje ogljika, ker zmanjšuje asimilacijo ogljikovega dioksida skozi stomatalne pore. Indeks listne površine je po najnovejših dognanjih (van Dijk in Bruijnzeel, 2001a; b) eden od pomembnejših parametrov modeliranja izhlapevanja prestreženih padavin.

world (Table 1). Most studies were carried out for coniferous forests in different climates (Chen *et al.*, 1991; Law *et al.*, 2001; Thomas & Winner, 2000), fewer for deciduous forests (Chason *et al.*, 1991; Le Dantec *et al.*, 2000; McPherson & Peper, 1998), and tropical forests (Clough *et al.*, 2000; Maass *et al.*, 1995; Nebel *et al.*, 2001; Schellekens, 2000). Leaf area index is highly variable in terms of time and space. For the deciduous forest the *LAI* changes seasonally and is highest during the growing period and during dormant period (in Slovenia in winter). Considering the time variability is important in understanding the differences in physical and biological processes of the ecosystem (such as evaporation). Spatial variability of leaf area index is mainly the result of different conditions for growth. *LAI* also changes within any ecosystem, depending on the given conditions. The connection between leaf area index and available water capacity has been proven in several studies (Le Dantec *et al.*, 2000; Maass *et al.*, 1995). The lack of water does not only reduce the leaf area, but also the abundance of leaves. Drought exerts a major influence on leaf area directly by influencing growth and indirectly on the carbon balance, since it reduces the assimilation of carbon dioxide through stomatal pores. According to latest studies (van Dijk & Bruijnzeel, 2001a; b), leaf area index should be considered as one of the most important parameters of modelling of evaporation of intercepted precipitation.

Preglednica 1. Pregled vrednosti *LAI* iz različnih raziskovalnih študij.

vrsta vegetacije	LAI	metoda	lokacija	avtor
listopadni gozd (hrast) listopadni gozd (bukev)	0,5–7,0 2,9–8,1	optična	Francija	Le Dantec *et al.* (2000)
listopadni gozd	4,9	neznana	Nizozemska	Lankreijer *et al.* (1993)
listopadni gozd (bukev)	7,4	PAR	Nizozemska	Bartenlink (1998)
listopadni gozd (hrast)	7,6	PAR	Nizozemska	Bartenlink (1998)
listopadni gozd (hrast)	1,7–2,0	fotografiranj e	Škotska	van Gardingen *et al.* (1999)
listopadni gozd (hrast, hikori)	4,9 3,8 2,9	zbiranje listja PAR optična	Tennessee	Chason *et al.* (1991)
listopadni gozd (javor, hrast)	4,4–8,4	zbiranje listja	Wisconsin	Fassnacht *et al.* (1997)
listopadni gozd (hrast)	4,4	sekanje	Kalifornija	Karlik & McKay (2002)

listopadni gozd (odprti)	3,1–3,7 3,3 0,9 3,7 3,4	sekanje optične PAR fotografiranj e alometrična	Kalifornija	McPherson & Peper (1998)
listnati gozd (nasad)	3,3 3,2–5,2 2,1–3,2 2,7–6,6	zbiranje listja PAR optična fotografiranje	Kalifornija	Martens *et al.* (1993)
listnati gozd (mangrovec)	3,3–4,9	zbiranje listja	Vietnam	Clough *et al.* (2000)
mešani gozd	1,6–4,4	zbiranje listja	Wisconsin	Fassnacht *et al.* (1997)
nasad oljk	0,3–4,8	zbiranje listja	Španija	Gomez *et al.* (2001)
listnati zimzeleni gozd (evkaliptus)	2,7	neznana	Portugalska	Valente *et al.* (1997)
listnati zimzeleni gozd (evkaliptus)	1,1 1,1	sekanje alometrična	Avstralija	Whitford *et al.* (1995)
listnati zimzeleni gozd (lovor)	7,8	neznana	Tenerife	Aboal *et al.* (1999)
iglasti gozd	5,1–7,6	PAR	Nizozemska	Bartenlink (1998)
iglasti gozd	2,3	neznana	JZ Francija	Gash *et al.* (1995)
iglasti gozd	1,5–4	neznana	Francija	Loustau *et al.* (1992)
iglasti gozd	2,3	neznana	Francija	Lankreijer *et al.* (1993)
iglasti gozd	3,2	neznana	Portugalska	Valente *et al.* (1997)
iglasti gozd	4,8–9,0 3,3–5,3 2,9–7,0	PAR optična fotografiranje	Kalifornija	Martens *et al.* (1993)
iglasti gozd	3,6–4,8	fotografiranje	Kanada	Frazer *et al.* (2001)
iglasti gozd	1,6–4,8 2,0–6,3	optične alometrične	Kanada	Chen *et al.* (1997)
iglasti gozd	1,5–2,5 1,7–3,3	sekanje optična	Kanada	Chen (1996)
iglasti gozd	3,8–4,6 3,8–4,5	optična fotografiranje	Kanada	Chen *et al.* (1991)
iglasti gozd	8,2–9,3	alometrična	Washington	Thomas & Winner (2000)
iglasti gozd	1,3 1,7 3,7 3,5	optična PAR alometrična zbiranje listja	Oregon	Law *et al.* (2001)
iglasti gozd	1,4–2,5	zbiranje listja	Wisconsin	Fassnacht *et al.* (1997)
tropski listnati gozd	4,2 5,1	zbiranje listja PAR	Mehika	Maass *et al.* (1995)
tropski gozd (akacija)	6,8–8,1	neznana	Indonezija	Bruijnzeel & Wiersum (1987)
tropski deževni gozd	4,2–4,4	zbiranje listja	Peru	Nebel *et al.* (2001)

Table 1. Overview of LAI *values from different research studies.*

Forest type	LAI	Method	Location	Author
Deciduous forest (oak) Deciduous forest (beech)	0,5–7,0 2,9–8,1	LAI-2000	France	Le Dantec *et al.* (2000)
Deciduous forest	4,9	unknown	Netherlands	Lankreijer *et al.* (1993)
Deciduous forest (beech)	7,4	PAR	Netherlands	Bartenlink (1998)
Deciduous forest (oak)	7,6	PAR	Netherlands	Bartenlink (1998)
Deciduous forest (oak)	1,7–2,0	photography	Scotland	van Gardingen *et al.* (1999)
Deciduous forest (oak, hickory)	4,9 3,8 2,9	litterfall PAR optical	Tennessee	Chason *et al.* (1991)
Deciduous forest (maple, oak)	4,4–8,4	litterfall	Wisconsin	Fassnacht *et al.* (1997)
Deciduous forest (oak)	4,4	destructive	California	Karlik & McKay (2002)
Deciduous forest (open)	3,1–3,7 3,3 0,9 3,7 3,4	destructive optical PAR photography allometric	California	McPherson & Peper (1998)
Deciduous forest (orchard)	3,3 3,2–5,2 2,1-3,2 2,7-6,6	litterfall PAR optical photography	California	Martens *et al.* (1993)
Deciduous forest (mangrove)	3,3–4,9	litterfall	Vietnam	Clough *et al.* (2000)
Mixed forest	1,6–4,4	litterfall	Wisconsin	Fassnacht *et al.* (1997)
Olive trees orchard	0,3–4,8	litterfall	Spain	Gomez *et al.* (2001)
Deciduous evergreen forest (eucalyptus)	2,7	unknown	Portugal	Valente *et al.* (1997)
Deciduous evergreen forest (eucalyptus)	1,1 1,1	destructive allometric	Australia	Whitford *et al.* (1995)
Deciduous evergreen forest (laurel)	7,8	unknown	Tenerife	Aboal *et al.* (1999)
Coniferous forest	5,1–7,6	PAR	Netherlands	Bartenlink (1998)
Coniferous forest	2,3	unknown	SW France	Gash *et al.* (1995)
Coniferous forest	1,5–4	unknown	France	Loustau *et al.* (1992)
Coniferous forest	2,3	unknown	France	Lankreijer *et al.* (1993)
Coniferous forest	3,2	unknown	Portugal	Valente *et al.* (1997)
Coniferous forest	4,8–9,0 3,3–5,3 2,9–7,0	PAR optical photography	California	Martens *et al.* (1993)
Coniferous forest	3,6–4,8	photography	Canada	Frazer *et al.* (2001)
Coniferous forest	1,6–4,8 2,0–6,3	optical allometric	Canada	Chen *et al.* (1997)

Coniferous forest	1,5–2,5 1,7-3,3	destructive optical	Canada	Chen (1996)
Coniferous forest	3,8–4,6 3,8–4,5	optical photography	Canada	Chen *et al.* (1991)
Coniferous forest	8,2–9,3	allometric	Washington	Thomas & Winner (2000)
Coniferous forest	1,3 1,7 3,7 3,5	optical PAR allometric litterfall	Oregon	Law *et al.* (2001)
Coniferous forest	1,4–2,5	litterfall	Wisconsin	Fassnacht *et al.* (1997)
Tropical deciduous forest	4,2 5,1	litterfall PAR	Mexico	Maass *et al.* (1995)
Tropical forest (acacia)	6,8–8,1	unknown	Indonesia	Bruijnzeel & Wiersum (1987)
Tropical rain forest	4,2–4,4	litterfall	Peru	Nebel *et al.* (2001)

3. MERITVE LAI NA RAZISKOVALNIH PLOSKVAH

V sodelovanju z univerzo iz Amsterdama sta bili konec leta 1999 izbrani dve merski raziskovalni ploskvi v gozdu, ena na severnem pobočju v podpovodju Rokave (1420 m^2), druga na južnem pobočju v podpovodju Dragonje (615 m^2), obe približno enako (2500 m) oddaljeni od vasice Labor, na nadmorski višini približno 200 m in v majhni medsebojni oddaljenosti (400 m) (slika 3). Na območju platoja Pleševica, med vasico Labor in izbranima merskima ploskvama je lepo viden časovni potek zaraščanja z gozdom. Z oddaljevanjem od Laborja srečamo tako na platoju 4–5, 10, 15–20 let stare sestoje in na koncu 30–35 let star gozd na strmih pobočjih (okrog 30^0), ki se spuščajo do dolin Rokave in Dragonje in na katerih sta bili izbrani omenjeni merski ploskvi (Šraj, 2003).

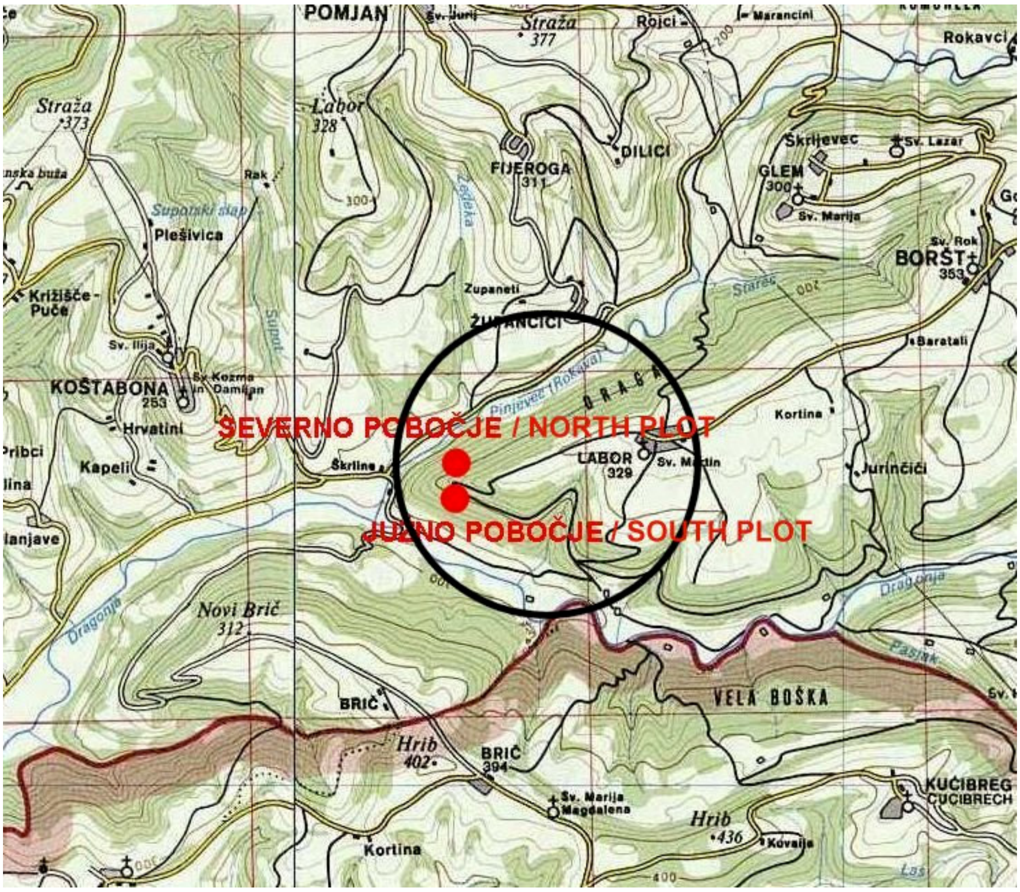
Zaradi določitve lastnosti in sestave obeh gozdnih ploskev, so bila na vsaki od njiju oštevilčena vsa drevesa s premerom na višini 1,35 m (*DBH*, angl. orig. tree diameter at breast height) večjim od 3 cm. Vsakemu drevesu posebej je bila nato določena vrsta in premer na višini 1,35 m z merskim trakom natančnosti 0,1 cm (te Linde, 2001). Določene so bile štiri najpogostejše vrste dreves: hrast (*Quercus pubescentis*), gaber (*Carpinus orientalis croaticus*), javor (*Sorbus torminolis*) in jesen (*Fraxinus ornus*) in kasneje dodan še

3. MEASURING LAI ON RESEARCH PLOTS

In co-operation with the Vrije Universiteit, Amsterdam, two measuring research plots were chosen at the end of 1999, one on the northern slope of the subwatershed of the Rokava (1420 m^2), the other on the southern slope in the subwatershed of the Dragonja (615 m^2), both situated approximately the same distance from the village of Labor, at an altitude of 200 m and short mutual distance (400 m) (Figure 3). In the area of the Pleševica plateau, between the village of Labor and the chosen plots the temporal course of forestation is well evident. By increasing the distance from Labor, forests are 4–5, 10, 15–20 years old and in the steepest slopes (around 30^0) 30–35 years old, descending into the valleys of the Rokava and Dragonja Rivers and into the sites of the chosen plots (Šraj, 2003).

Due to establishing the features and composition of both forest plots, all trees with a diameter of more than 3 cm at 1.35 m breast height (*DBH*) were numbered. Each tree was classified according to its species and diameter at the height of 1.35 m measured with measuring tape of 0.1 cm accuracy (te Linde, 2001). The four most frequent tree species were estimated: pubescent oak (*Quercus pubescentis*), hornbeam (*Carpinus orientalis croaticus*), maple (*Sorbus torminolis*), and ash (*Fraxinus ornus*); cornelian cherry dogwood rumeni dren (*Cornus Mas*). Na severni ploskvi je bila vsakemu drevesu s klinometrom in merskim trakom izmerjena tudi višina. Na južni ploskvi pa je gostota vegetacije prevelika, zato ni bilo mogoče ločiti posameznih drevesnih krošenj. Povprečna višina dreves na južni strani je bila ocenjena vizualno.

(*Cornus Mas*) was added later. On the north plot, height was measured with clinometer and measuring tape. On the south plot, however, vegetation density was too high, thus tree canopies could not be distinguished from one another. Mean tree height on the south plot was estimated visually.



Slika 3. Položaj raziskovalnih ploskev (vir: Interaktivni atlas Slovenije).
Figure 3. Position of research plots (source: Interactive Atlas of Slovenia).

3.1 SEVERNA RAZISKOVALNA PLOSKEV

Severna gozdna ploskev ima površino 1419 m^2. Na površini je bilo septembra 2000 naštetih 117 dreves s premerom (*DBH* na 1,35m) ≥ 3 cm (preglednica 2). Gostota dreves je torej 0,08 drevesa na kvadratni meter. Skoraj polovico dreves predstavlja kraški gaber (*Carpinus orientalis croaticus*) (47%), sledi hrast puhovec (*Quercus pubescentis*) (34%), jesen (*Fraxinus ornus*) (5%), javor (*Sorbus torminolis*) (3%) in ostale vrste (11%). Med ostalimi vrstami prevladuje rumeni dren

3.1 THE NORTH PLOT

The surface area of the north plot is 1419 m^2. There were 117 trees with a diameter at breast height (*DBH* at 1.35 m) ≥ 3 cm, counted in September 2000 (Table 2). This resulted in a stem density of 0.08 trees per square metre of forest floor. Hornbeam (*Carpinus orientalis croaticus*) represents almost half of all trees (47 %), followed by pubescent oak (*Quercus pubescentis*) (34 %), ash (*Fraxinus ornus*) (5 %), maple (*Sorbus torminolis*) (3 %), and other species (11 %). Among other species, cornelian cherry dogwood (*Cornus Mas*)

(*Cornus Mas*), ki je bil izločen naknadno. Kot podrastje se v večji meri pojavlja bodeča lobodika (*Ruscus aculeatus*). Povprečna višina dreves je 12,3 (± 5,1) m in povprečen premer vseh vrst dreves (*DBH* na 1,35 m) 13,8 (± 7,83) cm (preglednica 2). Povprečen premer hrastovih dreves je 17,6 (± 10,3) cm in gabrovih 10,9 (± 4,3) cm (te Linde, 2001).

prevails, which was added subsequently. The undergrowth is dominated by butcher's broom (*Ruscus aculeatus*). Mean tree height was 12.3 m (± 5.1) and mean *DBH* of all species 13.8 (± 7.83) cm (Table 2) (Te Linde, 2001). The mean *DBH* of oak trees was 17.6 (± 10.3) cm and hornbeam trees 10.9 (± 4.3) cm (te Linde, 2001).

Preglednica 2. Značilnosti posameznih vrst dreves na severni raziskovalni ploskvi.

	hrast	**gaber**	**javor**	**jesen**	**drugo**	**skupaj**
št. dreves	40	55	3	6	13	117
št. dreves [%]	34.19	47.01	2.56	5.13	11.11	100.00
gostota dreves [dreves/m^2]	0.0282	0.0388	0.0021	0.0042	0.0092	0.0824
povp. višina [m]	13.82	10.78	13.75	11.02	14.46	12.32
st.dev. višine [m]	5.74	4.18	8.16	1.27	5.05	5.06
povp. DBH [cm]	17.67	10.92	15.12	11.03	15.07	13.80
st.dev. DBH [cm]	10.25	4.30	8.73	4.93	7.10	7.83

Table 2. Characteristics of trees on the north plot.

	oak	**hornbeam**	**maple**	**ash**	**other**	**total**
No. of trees	40	55	3	6	13	117
No. of trees [%]	34.19	47.01	2.56	5.13	11.11	100.00
Stem density [trees/m^2]	0.0282	0.0388	0.0021	0.0042	0.0092	0.0824
Mean height [m]	13.82	10.78	13.75	11.02	14.46	12.32
St. dev. of height [m]	5.74	4.18	8.16	1.27	5.05	5.06
Mean DBH [cm]	17.67	10.92	15.12	11.03	15.07	13.80
St. dev. of DBH [cm]	10.25	4.30	8.73	4.93	7.10	7.83

3.2 JUŽNA RAZISKOVALNA PLOSKEV

Južna gozdna ploskev ima površino 615 m^2, kar je približno polovica velikosti severne ploskve. Kljub manjši površini pa število dreves na južni ploskvi (191) presega število dreves na severni ploskvi (preglednica 3). Gostota dreves je več kot trikrat večja (0,31 dreves na kvadratni meter) od gostote na severni ploskvi. Višina vsakega posameznega drevesa ni bila izmerjena zaradi prevelike gostote dreves, bila pa je ocenjena na 8 m v povprečju. Več kot polovico dreves predstavlja jesen (*Fraxinus ornus*) (54 %), sledi hrast (*Quercus pubescentis*) (26 %), kraški gaber

3.2 THE SOUTH PLOT

The south plot has an area of 615 m^2 or approximately half the size of the north plot. Nevertheless, the number of counted trees on the south plot (191) exceeded the number of trees in the north plot (Table 3). The stem density was about three times higher (0.31 trees per square metre) than in the north plot. The tree height could not be measured for each separate tree because of the high tree density but it was estimated at 8 m in average. More than half of the trees are ash trees (*Fraxinus ornus*) (54 %), followed by oak (*Quercus pubescentis*) (26 %), hornbeam (*Carpinus*

(*Carpinus orientalis croaticus*) (4 %), javor (*Sorbus torminolis*) (2 %) in ostale vrste (14 %). Tudi tu med ostalimi vrstami prevladuje rumeni dren (*Cornus Mas*), ki je bil izločen naknadno. Povprečen premer vseh vrst dreves (*DBH* na 1,35 m) je 7,14 (± 4,84) cm. Povprečen premer (*DBH*) jesenovih dreves je 4,7 (± 2,7) cm in hrastovih 13,2 (± 4,0) cm (te Linde, 2001). Višina in premer dreves na južni ploskvi sta precej manjša kot na severni strani.

orientalis croaticus) (4 %), maple (*Sorbus torminolis*) (2 %), and other species (14 %). Among other species the cornelian cherry dogwood (*Cornus Mas*) prevails, which was added subsequently. The mean DBH (at 1.35 m) of all species was 7.14 (± 4.84) cm. The mean DBH for ash trees was 4.7 (± 2.7) cm and for the oak trees 13.2 (± 4.0) cm (te Linde, 2001). Tree height and tree diameter on the south plot are both lower than in the north plot.

Preglednica 3. Značilnosti posameznih vrst dreves na južni raziskovalni ploskvi.

	hrast	gaber	javor	jesen	drugo	skupaj
št. dreves	50	7	4	104	26	191
št. dreves [%]	26.18	3.66	2.09	54.45	13.61	100.00
gostota dreves [dreves/m^2]	0.081	0.011	0.007	0.169	0.042	0.311
povp. DBH [cm]	13.17	5.80	6.21	4.69	5.55	7.14
st. dev. DBH [cm]	4.02	3.61	2.57	2.70	3.53	4.84

Table 3. Characteristics of tree species on the south plot.

	oak	hornbeam	maple	ash	other	total
No. of trees	50	7	4	104	26	191
No. of trees [%]	26.18	3.66	2.09	54.45	13.61	100.00
Stem density [trees/m^2]	0.081	0.011	0.007	0.169	0.042	0.311
Mean height [m]	13.17	5.80	6.21	4.69	5.55	7.14
St. dev. of height [m]	4.02	3.61	2.57	2.70	3.53	4.84

3.3 MERJENJE *LAI* NA RAZISKOVALNIH PLOSKVAH

Na vsaki od merskih ploskev so se poleg meritev posameznih komponent gozdnega hidrološkega kroga izvajale tudi tri različne meritve indeksa listne površine.

3.3.1 Določitev specifične listne površine SLA

Za izračun indeksa listne površine po neposredni metodi je potrebno najprej določiti specifično površino listov *SLA*. *SLA* je odnos med površino in maso suhih listov oziroma je površina listov na enoto mase [m^2/kg]. *SLA* se je določila za pet najbolj tipičnih drevesnih vrst na vsaki ploskvi posebej (hrast, gaber,

3.3 MEASURING *LAI* ON RESEARCH PLOTS

Besides measuring the single elements of forest hydrological cycle, on each plot three different measurements of *LAI* were performed.

3.3.1 Specific leaf area estimation SLA

For calculating leaf area index, first the specific leaf area *SLA* should be determined. *SLA* is the relationship between area and mass of dry leaves, i.e. *SLA* is leaf area over mass unit [m^2/kg]. *SLA* was determined for five most typical tree species for each plot separately (oak, horbneam, mapel, ash, jesen, javor, rumeni dren) poleg tega pa tudi za kategorijo "ostali listi" ter za droben listni material. Za vsako vrsto dreves je bilo nabranih približno 100–300 že razvitih svežih listov. Še svežim listom se je določila njihova površina. Površina je bila določena s pomočjo skeniranja posameznih listov (resolucija 300 dpi) in digitalno obdelavo ter analizo dobljenih slik. Posamezne zbirke listov so se potem posušile, najprej na zraku, potem pa še v sterilizatorju na 70 ^{0}C (Sterilizator S-45, UL Biotehniška fakulteta) do konstantne mase. Posušeno listje se je stehtalo (tehtnica Sartorius BP 310 S, d = 0,001g, UL Biotehniška fakulteta) do 0.001g natančno (Šraj, 2003). Z izračunom razmerja med površino listov in maso posušenih listov pa se je določilo *SLA* za vsako vrsto dreves posebej.

3.3.2 Zbiranje in določanje količine odpadlega listja

Zbiranje odpadlega listja se je izvajalo 2 leti, in sicer v sezoni 2000/01 (Vrije Universiteit Amsterdam) ter 2001/02, pri čemer so se v drugem letu meritve izvajale pogosteje in natančneje. Izločena je bila nova drevesna vrsta, rumeni dren. Listje se je na vsaki ploskvi posebej zbiralo v 10 košarah površine 0,2 m^2 (0,55 * 0,37 m), prekritih z mrežo (slika 4), in ročno pobiralo približno dvakrat mesečno. Mreža je bila rahlo napeta na košare približno 30 cm od tal, kar je preprečevalo dostop različnim listojedim živalim, hkrati pa zagotavljalo tudi dreniranje padavin, da ujeto listje ni gnilo, in zmanjševalo možnost odpihovanja listja. Košare so bile po ploskvah razporejene naključno in se med raziskavo niso premikale. Vsaka košara je bila oštevilčena, in sicer od 1 do 10 na severni ploskvi in od 11 do 20 na južni ploskvi. Pri vsakem pobiranju so se vzorci shranjevali v plastične vrečke z oznako številke košare in datumom. Pobrani vzorci iz posameznih košar so se vsakič posušili, najprej na zraku, nato pa v sterilizatorju pri 70 ^{0}C (Sterilizator S-45, UL Biotehniška fakulteta; slika 27a) do konstantne teže. Posušeno listje se je potem razvrščalo po posameznih vrstah dreves za vsako košaro posebej in stehtalo (tehtnica Sartorius BP 310 S, d = 0,001g, UL Biotehniška fakulteta; slika 27b) do 0,001 g

dogwood), and also for the category "other leaves" and fine foliage material. For each tree species, around 100–300 of developed new leaves were gathered. The leaf area was estimated for fresh leaves. Scanning of fresh leaves (with 300 dpi resolution), digital processing and analysis of images was performed. Collected sets of leaves were then dried, first air-dried and then oven-dried at 70^{0}C (Sterilizer S-45, UL Biotehnical Faculty) to the constant mass. The dried leaves were weighed (scale Sartorius BP 310 S, d = 0.001 g, UL Biotehnical Faculty) up to 0.001 g accuracy (Šraj, 2003). By calculating the relationshop between leaf area and mass of dried leaves *SLA* was estimated for each species separately.

3.3.2 Litterfall collection and estimation

Litterfall collection was performed for 2 years, i.e. in seasons 2000/01 (Vrije Universiteit Amsterdam) and 2001/02; measurements during the second season were performed more frequently and accurately. The new tree species, the cornelian cherry dogwood, was excluded from the measurements. The leaves were collected on each plot separately in 10 baskets of an area of 0.2 m^2 (0.55 * 0.37 m), which were covered with a net (Figure 4), and manually collected about twice monthly. The net was slightly tensioned on the baskets, approximately 30 cm above the ground, which prevented access to various foliage consumers and at the same time ensured drainage to prevent decay and reduced the possibility of leaves being blown away. Baskets were randomly distributed on the plots and were not moved during the study. Each basket was numbered, i.e. from 1 to 10 on the north plot and from 11 to 23 on the south plot. During each collection the samples were stored into plastic bags with an indication of the basket number and date. Each time, the collected samples were dried, first air-dried and then oven-dried at 70^{0}C (Sterilizer S-45, UL Biotehnical Faculty, Figure 27a) to their constant weight. The dried leaves were then classified according to their species for each basket separately, and weighed (scale Sartorius BP 310 S, d = 0.001g, UL Biotehnical Faculty, natančno. Posebej se je izločalo in tehtalo tudi semena oz. plodove ter odpadle vejice. Iz količine odpadlega listja [kg/m2] in specifične površine listov *SLA* se je izračunal indeks listne površine *LAI* (Šraj, 2003).

Figure 27b) up to 0.001 g of accuracy. Seeds, fruits and twigs were screened and weighed separately. From the quanity of fallen leaves [kg/m2] and specific leaf area *SLA*, leaf area index *LAI* was calculated (Šraj, 2003).

Slika 4. Košara za zbiranje odpadlega listja.
Figure 4. Basket for collecting litterfall.

3.3.3 Hemisferično fotografiranje

Fotografiranje drevesnih krošenj se je izvajalo na vsaki ploskvi v istih desetih točkah, kjer so bile postavljene tudi košare za zbiranje listja za določitev indeksa listne površine. Izvajalo se je 2 leti, in sicer v sezoni 2000/01 (Vrije Universiteit Amsterdam) ter 2001/02. V prvi sezoni so bile krošnje slikane petkrat v obdobju od 27. 9. 00 do 26. 10. 00. V drugi sezoni pa prav tako petkrat le v daljšem časovnem obdobju (7. 9. 01 do 9. 1. 02). Uporabljen je bil fotoaparat Minolta z 28 mm objektivom. Fotoaparat se je pritrdil na stojalo in v vsaki točki postavil v vodoravno lego ter usmeril proti severu. Fotografiralo se je z osvetlitvijo, povečano za 2 stopnji (2+), relativno glede na avtomatsko določeno osvetlitev fotoaparata pod krošnjami, da bi dobili čim boljši kontrast med nebom in krošnjami (Chen *et al.*, 1991).

3.3.3 Hemispherical photography

For estimating *LAI*, photography of tree canopies was performed on each plot at the same ten points, where the baskets for leaf collection were positioned. The measurements were performed for 2 years, i.e. in seasons 2000/01 (Vrije Universiteit Amsterdam) and 2001/02. During the first season, the canopy was photographed 5 times in the period from Sept. 27, 2000, to Oct. 26, 2000. In the second season, the canopy was also photographed 5 times, however, during a longer time period (from Sept. 9, 2001, to Jan. 9, 2002). Minolta camera with a 28 mm lens was used. The camera was fixed onto a stand, positioned horizontally at each point and directed towards north. To achieve the optimal contrast between the sky and canopy, the brightness was plus 2 (2+) relative to the automatically set brightness

V večini študij je za hemisferično fotografiranje uporabljena posebna širokokotna leča ″ribje oko" (fish-eye) z vidnim poljem 180^0 (Diaci *et al.*, 1999; Frazer *et al.*, 2001; Martens *et al.*, 1993; Silbernagel in Moeur, 2001; Walter in Torquebiau, 2000). Z njo lahko preslikamo krošnje iz poloble v naravi v krog na ravnini. Ker take leče nismo imeli na razpolago, smo uporabili lečo z ožjim vidnim poljem. Kakorkoli pa je Chen s sodelavci (1997) v svoji raziskavi ugotovil, da lahko pri velikih zenitnih kotih pride do podcenjevanja deleža odprtin v krošnji, kot posledica premajhne kotne resolucije in temnejšega neba v bližini horizonta. Oboje skupaj je vzrok, da pri obdelavi fotografije majhne odprtine pri velikih zenitnih kotih izgubimo.

Izdelane fotografije so bile potem skenirane z resolucijo 300 dpi in obdelane s programom Paint Shop Pro. Na vsaki fotografiji posebej se je ročno z različnimi orodji programa postopoma iskala meja med nebom in krošnjo, na koncu pa se je fotografija spremenila v 1-bitno sliko (črno-belo). S pomočjo histograma je bil potem določen delež belih oziroma črnih točk in s tem delež odprtin v krošnji. Ta se je potem uporabil za izračun prepusnosti krošenj za različne zenitne kote. Pri širokokotnih lečah se ponavadi za izračun *LAI* uporabi pet zenitnih kotov (7, 23, 38, 53 in 68^0; Chason *et al.*, 1991; Chen *et al.*, 1991). Ker je bil pri nas uporabljen 28 mm objektiv, sta bila pri izračunu uporabljena le zenitna kota 7^0 in 23^0 (Šraj, 2003).

3.3.4 Fotosintetsko aktivno sevanje (PAR)

Meritve *PAR* so bile narejene s Sunflect Ceptometrom (Vrije Universiteit Amsterdam). Merilo se je sevanje nad in pod krošnjami na južni ploskvi oktobra 2000. Na severni ploskvi meritev ni bilo mogoče izvesti, ker skozi krošnje dreves ni prehajalo skoraj nič sončne svetlobe. *PAR* pod krošnjami se je merilo v istih desetih točkah, kjer so bile posnete tudi fotografije, nad krošnjami pa na bližnji gozdni jasi. Narejene so bile tri meritve leta 2000 (Vrije Universiteit Amsterdam), in sicer 16., 21., in 22. oktobra v jasnih vremenskih razmerah. Vsaka meritev je v povprečju obsegala 80 individualnih meritev na 80 fotodiodah Ceptometra, za 8 azimutnih

of the camera below canopy (Chen *et al.*, 1991).

In most studies a special wide angle fish-eye lens is used with 180^0 field-of-view (Diaci et al., 1999; Frazer *et al.*, 2001; Martens *et al.*, 1993; Silbernagel and Moeur, 2001; Walter and Torquebiau, 2000). The lens helps us copy the canopy from the hempishere in the nature into a circle in plane. Since no such lens was at our disposal, we used a lens with a narower field-of-view. However, Chen *et al.* (1997) established that in large zenith angles an underestimation of the gap canopy fraction can occur as a consequence of too small angle resolution and darker sky near the horizon. This is the reason that during processing the small gaps with large zenith angles are lost.

The photographs are then scanned with a 300 dpi resolution and processed with Paint Shop Pro. By using different program tools, on each separate photo the border between sky and canopy was determined manually, and at the end the photo was changed into a 1-bit (black and white) photo. With a histogram the ratio of white and black points (and thus canopy gaps) was estimated. The ratio was then used for calculating the transmission of the canopy for different zenith angles. With wide-angle lens, 5 zenith angles are usually used (7, 23, 38, 53 and 68^0; Chason *et al.*, 1991; Chen *et al.*, 1991). Since a 28 mm lens was used in our case, only the zenith angles 7^0 and 23^0 were used (Šraj, 2003).

3.3.4 Photosynthetically active radiation (PAR)

PAR measurements were made using Sunflect Ceptometer (Vrije Universiteit Amsterdam). Incident and transmitted *PAR* was measured in the south plot in October 2000. Measurements could not be performed on the north plot, since almost no sun light was transmitted throught the tree canopy. Transmitted *PAR* was measured in the same ten points, where the photographs were taken, incident *PAR* was measured on a close-by forest clearing. Three measurements were made in 2000 (Vrije Universiteit Amsterdam), i.e. on October 16, 21 and 22 in clear weather conditions. On average, each measurement comprised 80 individual measurements on 80 photodiodes of the Ceptometer, for 8 azimuth orientacij. Vsak izmerjeni podatek predstavlja torej integracijo 8 x 80 = 640 točkovnih meritev (te Linde, 2001).

4. ZAKLJUČKI

Indeks listne površine se je določal po treh metodah, in sicer z neposredno metodo zbiranja in določanja količine odpadlega listja ter z dvema posrednima metodama: hemisferičnim fotografiranjem drevesnih krošenj in z merjenjem fotosintetskega aktivnega sevanja *PAR* na vsaki ploskvi posebej, saj se opazno razlikujeta tako v strukturi, gostoti in velikosti dreves kot v sami sestavi.

Vse tri metode so med seboj zelo različne. Pri merjenju *PAR* s Ceptometrom dobimo rezultate skoraj takoj. Hemisferično fotografiranje krošenj je v fazi fotografiranja dokaj hitro, vendar kasnejša obdelava fotografij zahteva veliko časa in dela. Ima pa pred merjenjem *PAR* prednost v tem, da pri vsaki fotografiji upošteva različne zenitne kote in zajame precej velike površine. Direktna metoda zbiranja odpadlega listja pa je po vloženem času in delu najzahtevnejša od vseh treh, je pa zato tudi najbolj natančna.

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orientations. Thus, each measured data represents the integration of 8 x 80 = 640 point measurements (te Linde, 2001).

4. CONCLUSION

Leaf area index was estimated according to three methods, i.e. the direct method of literfall collection and estimation, and two indirect methods: hemispherical photography of the tree canopy and method of photosynthetically active radiation *PAR*. The measurements were performed on each plot separately, since they differ considerably in terms of structure, density, size and composition.

The three methods differ among each other. In *PAR* measurements with the Ceptometer the results are achieved immediately. Hemispherical photograpy is fairly fast in the phase of photographing, but the later processing is time-demanding and requires high work input. However, the main advantage of hemispherical photography over *PAR* is that it considers different zenith angles and includes fairly large areas. The direct method of litterfall collection is the most demanding in terms of time and work input, but it also produces the most accurate results.

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