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Surface layer characteristics and SVAT modelling of a fetch-limited forest

Ebba Dellwik

PhD thesis

Abstract

The work in this thesis concerns data evaluation and soil-vegetation-atmosphere-transfer (SVAT) modelling of measurements taken in and above a temperate beech forest canopy. The SVAT modelling framework used here has been a mixture of an electrical network analogy (single-layer model) and an analytical type of scheme where vertical gradients within the canopy are captured with continuous functions, which can be integrated to the ecosystem level.

The beech forest site is fetch limited and influence on forest mast measurements from upwind farmland was investigated. The influence was studied (1) by analyzing ratios of friction velocity taken at different heights in the mast as a function of fetch length and (2) by studying the flux-profile relationship of wind speed and momentum flux, and temperature and sensible heat flux, respectively. The flux-profile relationships also yielded information on the nature of the roughness sublayer which is the lowermost part of the surface layer. The results indicated that the forest site is influenced by the upwind conditions via internal boundary layers. The forest flux-profile relationships were interpreted in terms of aerodynamic resistances. Additional measurements yielded information on the viscous sublayer resistance for heat. Total atmospheric resistances for sensible heat and momentum were approximately equal.

Regarding the modelling of soil-vegetation-atmosphere interaction, the focus was on carbon dioxide exchange. A simple model was developed where leaf measurements taken at ambient conditions were used to construct a mean canopy light response curve, which was integrated to yield the carbon dioxide uptake into the tree crowns. In order to compare with the eddy-correlation measurements of net ecosystem exchange, models and measurements of the ecosystem respiration were included. Agreement between the eddy-correlation based estimate and the leaf-measurement based scheme was generally good. The radiation scheme for the integration (upscaling) does not include a distinction between direct and diffuse light.

Together with a simple model for the atmospheric resistances, temperature measurements and water vapor fluxes were analyzed to give estimates of mean canopy resistance. The derived estimates were compared to a canopy scale version of the optimal stomatal conductance hypothesis, which regards water lost via transpiration as a cost when assimilating carbon. An approach which calculates canopy photosynthesis analytically is also presented.

The work in this thesis represents an attempt to derive simple but accurate formulations for single-layer models of trace gas and heat exchange in forested areas.

Sammendrag på dansk

Denne afhandling omhandler dels analyser af en række forskellige målinger taget i og over en dansk bøgeskov, dels sammenligninger mellem disse målinger og modeller for stofudvekslingen mellem jorden, vegetationen og atmosfæren. I litteraturen betegnes det som SVAT (Soil Vegetation Atmosphere Transfer) modeller. Grundlaget for den SVAT modellering, der er anvendt her, er en blanding af en analogi til elektriske modstandsnetværk, også refereret til som enkeltlagsmodeller, og modeller, hvor vertikale gradienter af de stoffer der er af interesse, inden i såvel som over skoven, tilpasses de målte data i form af analytiske funktioner. Disse kan derefter integreres op til økosystemniveau.

Bøgeskoven har en begrænset udstrækning hvorved målingerne i den 57m hje meteorologiske mast er under indflydelse også af de landbrugsområder, der ligger uden for skoven. Indflydelsen blev undersøgt på to måder: (1) ved at sammenligne målinger af den turbulente friktionshastighed, u_*, i forskellige højder på masten. Effekten af skovens udstrækning viser sig ved at u_* aftager med højden på en måde, der afhænger af afstanden til skovkanten. (2) ved at studere sammenhængen mellem målte turbulente flukse og de tilhørende profiler af vindhastighed og temperatur. Disse fluks-profil-relationer giver også indblik i udstrækningen og strukturen af det nederste meget turbulente del af det atmosfæriske grænselag, tæt på trækronerne (the roughness sublayer). Resultaterne af analysen er at målingerne til en vis grad er influeret af opstrømsforholdene. Det interne grænselag, der udvikler sig fra skovkanten og nedstrøms, burde ideelt set være dybere, det vil sige at strækningen til skovkanten burde være lidt længere. Fluks-profil-relationerne blev fortolket i form af aerodynamiske modstande (elektrisk analogi). Supplerende målinger gav oplysninger om modstanden for varmetransport i de viskose sublag på de enkelte bladoverflader. Et overraskende resultat af undersøgelsen er at den totale atmosfæriske modstand for transport af varme og bevægelsesmængde er næsten ens.

Med hensyn til modelleringen af stoftransporten mellem jord, vegetations og atmosfære er hovedvægten lagt på udvekslingen af CO_2. Der er udviklet en simpel model, hvor kammermålinger på enkelte blade under nær naturlige temperatur og fugtighedsforhold er anvendt til at konstruere en funktion for fotosyntesens afhængighed af lysforholdene. Denne funktion er blevet integreret til at give det totale CO_2 optag for hele trækronen. For at kunne sammenligne dette resultat med netto-udvekslingen (net ecosystem exchange, NEE) af CO_2, som den måles med eddy-korrelationsmetoden, er det nødvendigt at tilføje modeller for økosystem respirationen. Disse er dels baseret på direkte målinger af jordrespirationen med kamre, dels på eddy-korrelationsmålinger såvel over som under kronelaget under natlige forhold. Generelt blev der fundet en god overensstemmelse mellem de to mder at beregne CO_2 optaget i kronelaget. Med hensyn til lysforholdene ned gennem kronelaget blev der ikke skelnet mellem diffus og direkte stråling.

Sammen med en simpel model af den atmosfæriske modstand for turbulent transport og målinger af vanddampfluksen og bladtemperaturen blev den gennemsnitlige stomata modstand for vanddamp og dermed CO_2 beregnet. Disse resultater blev derefter sammenlignet med en version af en model kaldet "the optimal stomatal conductance model", i hvilken det vand, der mistes ved transpiration gennem stomata, betragtes som en omkostning for at assimilere CO_2. En analytisk metode til beregning af kronetagets fotosyntese er også angivet.

Det underliggende princip i dette arbejde har været at udlede simple men dog tilstrækkeligt nøjagtige relationer for gas og varmeudvekslingen mellem atmosfæren og skovområder, således at det vil være muligt at indarbejde dem i dynamiske vejr og klimamodeller

Preface

This PhD thesis was written as part of the requirements for the PhD degree at the Technical University of Denmark. During the work with the thesis I have been enrolled at the department for Environment & Resources, Technical University of Denmark. Funding was provided by Risø National Laboratory (Roskilde, Denmark) and the Danish Research Academy.

The goal of the work presented in the thesis was to analyze long term and campaign measurement data from a Danish beech forest site using existing and new soil vegetation atmosphere transfer (SVAT) model relationships. The framework was an evaluated need for a very simple model that could run at an hourly time scale and be incorporated into larger scale (regional to global) atmospheric models. Hence, the focus for the modelling work was on the simpler parameterizations with the additional aim to - if possible - further reduce the number of variables and parameters involved.

All analyses were restricted to the period of full leaf area index, when the effect from the trees on the energy and carbon fluxes is the greatest.

In many cases, the work presented in this thesis has been the first attempt to seriously examine the measurement data, which is why a considerable attention is devoted to quality assessment. Since the forest site is fetch limited, most of the quality assessment has been to understand and quantify internal boundary layer influence on the measurements.

Data availability has to a high degree influenced the modelling work. Existing models, which require parameters that either were not, or could not, be easily acquired have been excluded. This exclusion reflects a deliberate choice to make the most of the existing, and in some cases already large, data bases rather than spending time and effort on new campaigns. Nevertheless, two measurement campaigns were initiated to achieve complementary information on atmosphere-canopy dynamics.

The first section of this thesis comprises an introduction to the field of SVAT modelling and a description of the measurement site in Sorø Lille Bøgeskov. Further, key results are presented and possibilities of future research discussed. This section was written keeping a reader in mind, who does not have an extensive knowledge of the field.

The second section of the thesis consists of four papers, that provide a more detailed theoretical background and method description, as well as the results and conclusions of data analysis and modelling.

Contents

Paper I: Dellwik E, Jensen NO. Internal equilibrium layer growth over forest, *Theor. Appl. Clim.*, 66:173-184, 2000.

Paper II: Dellwik E, Jensen NO. Flux-profile relationships over a fetch limited beech forest, *Bound-Layer. Meteorol.*, submitted, 2003.

Paper III: Dellwik E, Mikkelsen TN, Pilegaard K, Ro-Poulsen H. Scaling carbon dioxide uptake from leaf to crown in a temperate beech forest, *Tree Physiology*, submitted, 2003.

Paper IV: Dellwik E. Canopy conductance of a temperate beech forest compared to the optimal stomatal control hypothesis, report.

1   Introduction to SVAT modelling

A soil vegetation atmospheric transfer (SVAT) model is a scheme for predicting surface fluxes of a gas, heat or momentum flux between soil, vegetation and atmosphere. SVAT modelling is used for a wide variety of applications. Researchers in agriculture and forestry use SVAT models for prediction of crop growth. Meteorologists need accurate estimates of latent and sensible heat surface fluxes for weather predictions. Biologists want better understanding of how ecosystems function. Climatologists need estimates of how the surface and its vegetation may influence future climate, and hydrologists use SVAT modelling for water balance simulations at different scales. Each discipline has its own focus, which result in a great variety of models.

Within the last decade, the micro-meteorological community has developed many multi-layer models for use over forests (see for example Baldocchi and Harley, 1995, Williams *et al.*, 1996 and Gu *et al.*, 1999). A multi-layer model divides the canopy into several horizontally homogeneous layers with a typical depth of a tenth of total plant area/ground area (plant area index, PAI[1]). The canopy flux from a multi-layer model is the sum of the contribution from each layer. The main advantage with multi-layer models is the ability to properly parameterize vertical canopy structure and micro-climate. The disadvantage is that they are computationally and experimentally demanding (see Raupach and Finnigan, 1988, for a discussion). For example, a model for meteorological forecasting use about 30 layers to describe the atmosphere from the surface layer to beyond the tropopause. To add another 40 layers as a lower boundary condition would be unreasonable.

Single-layer models in contrast are very useful as a lower boundary condition in an atmospheric boundary layer model, but it is not a simple task to reduce canopy dynamics to a single source/sink layer. In between these two types of models are the two-layer models, which consider understorey and main canopy separately. Recent single layer models for climatological applications are the SiB2 model (Simple biosphere 2, Sellers *et al.*, 1996), MOSES (Met Office Surface Exchange Scheme, Cox *et al.*, 1999) and for meteorological forecasting the ISBA model (Interactive Soil Biosphere Atmosphere, Noilhan and Mahfouf, 1996).

A typical model scheme for a single layer SVAT - for the sensible and latent heat fluxes over a vegetated surface is presented in Figure 1. It uses an analogy between electrical networks and flux-gradient relationships, with concentrations, temperatures and wind speeds in the place of electrical potential, and fluxes of trace gases, water vapor, heat and momentum in the place of current. The resistances in a SVAT scheme are classified according to the nature of the transfer process described: (1) r_a describes the resistance to the flux in the *turbulent* surface layer, which is the lower part of the atmospheric boundary layer (typically the lowermost 1/10) where gradients are large, (2) r_b describes diffusion across the *viscous* boundary layer, which forms around each leaf and (3) r_c describes the *control by vegetation* on carbon dioxide uptake and water vapor loss from the leaves through micro-meter scale pores on the leaves called stomata. Processes within the canopy can not be described by the electrical network analogy, since turbulent length scales typically exceed modelling distances (Kaimal and Finnigan, 1994).

Development in the field of SVAT modelling for atmospheric applications has been driven by the concern for global warming due to enhanced levels of greenhouse gases in the atmosphere. The focus has been on carbon dioxide (CO_2), and since the Kyoto protocol was negotiated in 1997, the question of carbon uptake

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[1]PAI includes the area of non-photosynthezising tissue such as stems, in contrast to the leaf area index, LAI.
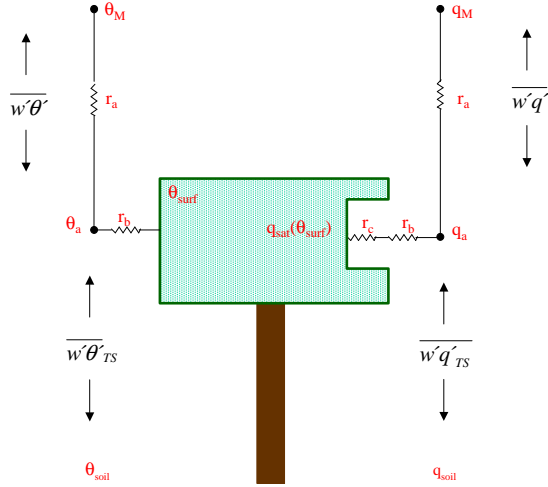
Figure 1. SVAT model scheme for latent and sensible heat transfer. Temperature and humidity are denoted θ and q respectively with subscripts M and a defining air properties at a measurement height above the canopy and in the canopy. The eddy covariance notation is used to denote turbulent fluxes $\overline{w'\theta'}$ and $\overline{w'q'}$, and subscript TS indicates the trunk space counterpart. The canopy radiation temperature is denoted θ_{surf} and the bulk humidity concentration of the stomata of the trees is $q_{sat}(\theta_{surf})$, where sat is the saturated vapor pressure.

in terrestrial ecosystems and especially forests has been high up on both the political and scientific agenda. Tans *et al.* (1990) investigated different terrestrial source/sink scenarios for carbon dioxide, and found that the best agreement with data and observations was found if imposing greater sinks in the northern than in the southern hemisphere. Attention was directed to the northern forests and subsequently a network of tower flux stations in European forests was setup in 1996 in the framework of the EUROFLUX project (see Aubinet *et al.*, 2000). The aim of EUROFLUX was to provide reliable long-term continuous measurement series of climatological and surface flux data. EUROFLUX was followed by its northern American counterpart AMERIFLUX in 1997. In 2001 the EUROFLUX and AMERIFLUX sites became members of a global network of flux measurement sites, FLUXNET (see Baldocchi *et al.*, 2001). FLUXNET encompasses over 200 measurement stations over all kinds of vegetation (April, 2003). Data from these flux sites are invaluable for SVAT-modellers.

The focus on carbon dioxide has led to a "greening" of the SVAT models with a new emphasis on biological processes. Even in SVAT models with the aim of modelling latent and sensible heat fluxes only, the biological processes are of growing interest, since it is recognized that plants lose water only as carbon is gained, *i.e.* in order to understand how the vegetation regulates the water losses to the atmosphere, it is essential to understand the carbon uptake. The work presented in this thesis use data from the Danish EUROFLUX site.

2 The resistance network

The nature of a SVAT resistance network for a single-layer model depends on the modelled constituent (Figure 2). The transfer of momentum (τ) is regulated only by the aerodynamic resistance and the lower boundary condition is $\bar{u} = 0\text{m/s}$. Within the canopy, momentum is absorbed by vegetation mainly by pressure forces, that have no counterparts in the transfer of heat and scalars (Thom, 1975, Kaimal and Finnigan, 1994). Transport of sensible heat (H) depend on two physical processes; the turbulent atmospheric process described by r_{ah} and molecular diffusion which is formalized in the viscous boundary layer resistance, r_{bh}. The mean surface temperature is θ_{surf}, which can be measured radiometrically. Latent heat (E), in case of dry leaves, is transpired through micrometer scale openings on the leaves called stomata, which is formalized in the canopy resistance, r_{cq}. The lower boundary condition in the latent heat transfer pathway is the mean water vapor concentration in the stomata, which is assumed saturated ($q_{sat}(\theta_{surf})$) and can be calculated from the Clausius-Clapeyron equation. Diffusion from the surface of the leaves to a measurement height in the atmosphere is described by the viscous boundary layer and aerodynamic resistances for water vapor r_{bq} and r_{aq}. In case the canopy is wet, water vapor is evaporated to the air from the canopy, and transpiration plays a minor role since the gradient $q_{sat} - q_a$ is very small. Hence the pathway for latent heat under wet conditions is the same as for sensible heat.

Carbon dioxide uptake in the crown (A_n or $A_{n,crown}$) is parameterized by the same resistances as latent heat under dry canopy conditions (r_{ac}, r_{bc} and r_{cc}). It is more difficult to model CO_2 uptake by the forest crowns than momentum and heat fluxes for mainly two reasons: (1) the stomatal CO_2 concentration is a function of CO_2 uptake in the crown and canopy resistance, and (2) the measured flux over the canopy can not be used directly to assess the CO_2 flux into the leaves since respiration from soil and woody tissue also contribute to the measured flux. These issues will be discussed more thoroughly in the r_c subsection below.

Mathematically, the resistance network for flux prediction can be formulated as follows;

$$
\left.
\begin{array}{l}
\frac{\tau}{\rho} = -\overline{u'w'} = \frac{\bar{u}_M - 0}{r_{am}} \\[4pt]
\frac{H}{\rho c_p} = \overline{w'\theta'} = -\frac{\bar{\theta}_M - \theta_{surf}}{r_{ah} + r_{bh}} \\[4pt]
\frac{E}{\rho \lambda} = \overline{w'q'} = -\frac{\bar{q}_M - q_{sat}(\theta)_{surf}}{r_{aq} + r_{bq} + r_{cq}} \\[4pt]
A_n = -\overline{w'c'} = \frac{\bar{c}_M - \bar{c}_i}{r_{ac} + r_{bc} + r_{cc}}
\end{array}
\right\}, \tag{1}
$$

where $\bar{u}$, $\bar{\theta}$, $\bar{q}$ and $\bar{c}$ are the mean values of wind speed, temperature, humidity and CO_2 concentration, subscript m denotes momentum and ρ, λ and c_p are the air density, heat of vaporization and heat capacity at constant pressure for dry air, respectively. Further, the eddy covariance notation for fluxes has been introduced with $\overline{u'w'}$ signifying the mean value of covariance between the horizontal and vertical (w) wind components.

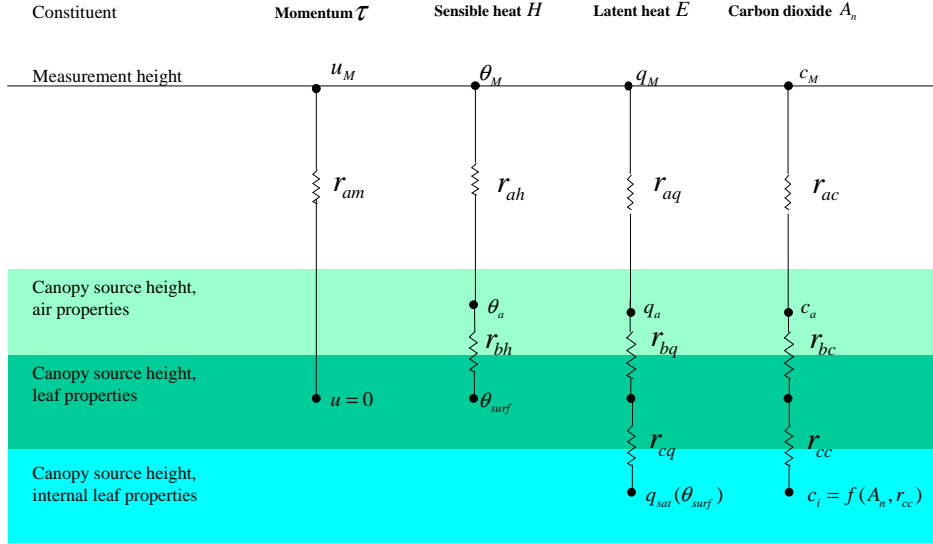| Constituent | Momentum τ | Sensible heat H | Latent heat E | Carbon dioxide A_n |

Figure 2. SVAT model scheme for momentum, sensible heat, latent heat and carbon dioxide originating/resulting in the canopy. The subscript M denotes the measurement height. The canopy model height or canopy source height (subscripts a, surf and i) represents the physical level in the canopy from which the fluxes in a one-layer model originate.

2.1 The aerodynamic resistance r_a

The aerodynamic resistances for momentum, carbon dioxide and sensible and latent heat transfer are defined as

$$
\left. \begin{array}{l}
r_{am} \equiv \dfrac{\bar{u}_M - 0}{u_*^2} \\[4pt]
r_{ah} \equiv \dfrac{\bar{\theta}_M - \bar{\theta}_a}{u_* \theta_*} \\[4pt]
r_{aq} \equiv \dfrac{\bar{q}_M - \bar{q}_a}{u_* q_*} \\[4pt]
r_{ac} \equiv \dfrac{\bar{c}_M - \bar{c}_a}{u_* c_*}
\end{array} \right\} ,
\tag{2}
$$

where the friction velocity $u_* = (\tau/\rho)^{1/2}$, $\theta_* = -H/(\rho c_p u_*)$, $q_* = -E/(\lambda \rho u_*)$ and $c_* = -\overline{w'c'}/u_*$ are the turbulent velocity scales for momentum, sensible and latent heat, and carbon dioxide, respectively.

Scaling arguments as well as a turbulent analogy to viscous diffusion theory (K-theory) has led to the following relationships being proposed for the surface layer;

$$
\frac{\partial \bar{u}}{\partial z} = \frac{u_*}{\kappa z} \phi_m
\tag{3}
$$

where z is height over the surface, $\kappa = 0.4$ is the von Karman constant and ϕ_m is a non-dimensional scaling function. In the upper part of the surface layer, the inertial sublayer (Figure 3), ϕ_m (and corresponding ϕ_h, ϕ_q and ϕ_c) can be expressed as functions of the ratio of z and atmospheric stability which is expressed with the Monin-Obukhov length ($L = (\theta_K u_*^2)/(\kappa g \theta_*)$, where θ_K denotes temperature in Kelvin and g the acceleration due to gravity). The Monin-Obukhov length defines the ratio between shear and convective production of turbulence in the surface layer. Formulation of the scaling functions has been achieved empirically using data from surface layer experiments over short vegetation in Australia, USSR and the USA in the 1960s and 70s (see Högström, 1988, for an overview and inter-comparison of the results). Equation 3 can be integrated to give a flux-profile relationship, which in turn forms the basis of many inertial sublayer formulations of the aerodynamic resistance.
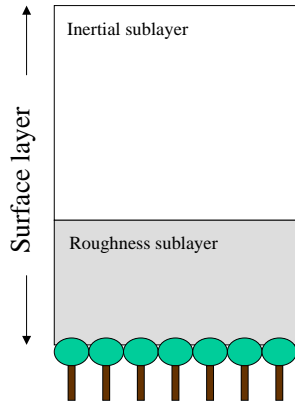
Figure 3. The surface layer can be subdivided into two sublayers, the roughness sublayer and the inertial sublayer. Over rough vegetation, like forest, the roughness sublayer is likely to extend above normal mast heights.

In the late 1970s, Garrat (1978) and Raupach (1979) independently showed that the inertial sublayer relationships did not apply for flow over forests. Interestingly, their estimated deviations from the inertial sublayer formulations were contradictory. These differences were later attributed to vegetation density; Garrat investigated flux-profile relationships over a low-density savannah, wheras Raupach was working with data taken over a dense pine forest. The part of the surface layer, where inertial sublayer theory does not apply is called the roughness sublayer. Depending on vegetation density, it extends 2-3 canopy heights above ground (see Cellier and Brunet, 1992, for a thorough description).

In the roughness sublayer, the ϕ functions are no more a universal function of z/L but they are also dependent on properties of the underlying canopy. Hence corrections to the inertial sublayer formulations are necessary.

In the inertial sublayer, r_{am}, r_{ah}, r_{aq} and r_{ac} can be assumed to be equal, whereas in the roughness sublayer, they can not. In 1996, Raupach, Finnigan and Brunet were able to explain some roughness sublayer features with a mixing layer analogy, where the roughness sublayer is seen as a transition layer between the canopy (characterized by a slow flow) and the inertial sublayer with a relatively much faster flow. In mixing layers, scaling functions for momentum, heat and scalars are different, which reflect in the aerodynamic resistance. The validity of gradient diffusion analogies in the roughness sublayer is questionable for *sparse* canopies, since canopy scale turbulence may cause counter-gradient fluxes.

2.2 The viscous sublayer resistance r_b

The viscous sublayer resistance parameterizes molecular diffusion across the boundary layers that form around each leaf in the canopy (see Figure 4). Relevant parameters in a parametrization for r_b are for example leaf dimensions, diffusivity of the constituent in question (or thermal diffusivity in case of sensible heat) in air, viscosity of air and plant area index. The variable in r_b parametrizations is most commonly u_*, approximating the wind speed in the canopy air space. The Schmidt number Sc defines the ratio between the kinematic viscosity of air (ν) and the diffusivity of a gas constituent in air (D) and the Prandtl number Pr defines the ratio between ν and thermal diffusivity D_T. The values of the Schmidt and Prandtl numbers for the constituents considered here are $Sc_q = 0.62$, $Sc_c = 1.0$ and $Pr_{air} = 0.71$. For water vapor transfer, Jensen and Hummelhøj (1995) sug-

gested

$$r_{bq} = Sc^{-1} \left[\frac{C_1}{PAI^2} \frac{lu_*}{\nu} \right]^{1/3} \frac{1}{u_*} \approx C_2 u*^{-2/3}, \qquad (4)$$

where C_1 is a constant, C_2 is weakly dependent on leaf dimensions (l) and plant area index. In a parametrization like Jensen's and Hummelshøj's, with r_b depending linearly on Sc^{-1} (Pr^{-1} for sensible heat transfer), r_b for water vapor and carbon dioxide can be calculated from

$$r_{bh} = 1.1 r_{bq} = 0.7 r_{bc}. \qquad (5)$$

Monteith and Unsworth (1990) present a more complicated deduction for r_b, by distinguishing between diffusivity in moving air flow and still air. However, their result

$$r_{bh} = 1.1 r_{bq} = 0.8 r_{bc} \qquad (6)$$

is similar to the results of Jensen and Hummelshøj.
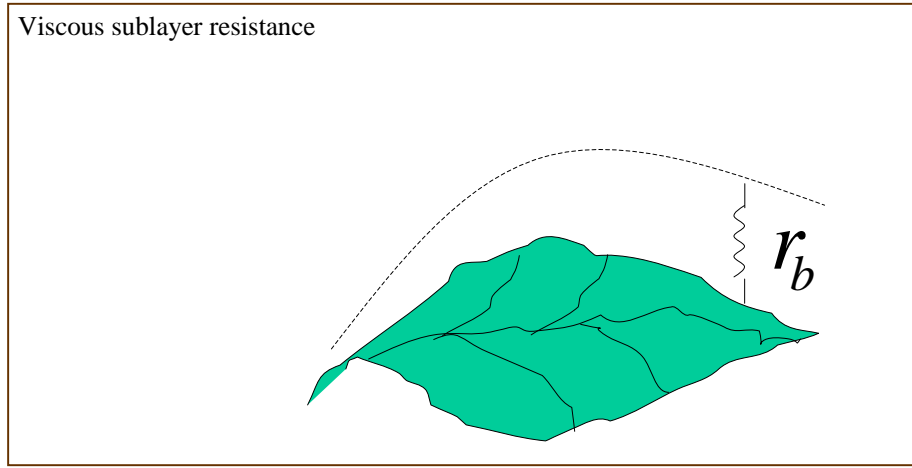

Viscous sublayer resistance

r_b

Figure 4. The viscous sublayer resistance r_b describes the scaled up process of molecular (or heat) diffusion through the viscous boundary layers which form around each leaf in the canopy.

The viscous sublayer resistance is sometimes confused with the so called excess resistance (commonly denoted the kB^{-1} factor). The necessity of an excess resistance arises when applying inertial sublayer flux-profile relationships to assess surface properties. The extrapolation of the inertial sublayer theory into the roughness sublayer causes a mismatch between reality and model. The excess resistance is introduced to overcome this flaw and is hence rather an empirical correction for the roughness sublayer than an alternative to r_b.

2.3 The canopy resistance r_c

Before the introduction of the "green" SVAT models, the most common parametrization of r_c was based on product of a minimum value and a number of functions, each describing the impact of individual environmental parameters on the stomata in the canopy. This type of function is easier to visualize when using the inverse of the resistance, the canopy conductance $g_c = 1/r_c$, i.e.

$$g_c = g_{c,max} \cdot f_1 \cdot f_2 \cdot f_3 ... \qquad (7)$$

where $g_{c,max}$ is the maximum canopy conductance and functions f_i range between 0 and 1, with value 1 indicating no environmental limitation. This type of model was first presented by Jarvis in 1976 on the leaf scale and has since been widely used (see Lynn and Carlson, 1990, for a review). However, when adding the CO_2 flux to the desired output parameters, this approach is inadequate because c_i (Eq 1 and Figure 2) is an unknown.

Leaf photosynthesis and respiration

The challenge to meet model requirements for CO_2 has lead to inclusion of photosynthesis models. Photosynthesis is a complicated biochemical process, in which energy from the sun is ultimately used to fix carbon that the plant can use for growth. Photosynthesis takes place in the chloroplasts of mesophyll cells (Figure 5). The mesophyll defines the internal cells in the leaves. The process of fixing carbon is called carboxylation and is for most plants described biochemically with the so called Calvin cycle. The first reaction in the Calvin cycle concerns the fixing of CO_2 to ribulose-bi-phosphate (RuBP), a five carbon sugar with two attached phosphate groups. This is called carboxylation. The resultant compound is split into two molecules, each containing three carbon atoms. Subsequent reactions form the product of the cycle, glyceraldehyde 3-phosphate, and finally RuBP is re-generated and free to accept a new CO_2 molecule. The enzyme which catalyzes the initial steps in the cycle is called RuBP carboxylase-oxygenase or Rubisco. The catalytic rate of most enzymes is strongly dependent on temperature, which is one cause of the temperature dependency of the phototsynthetic rate. (Raven, 1986, Nobel, 1991).
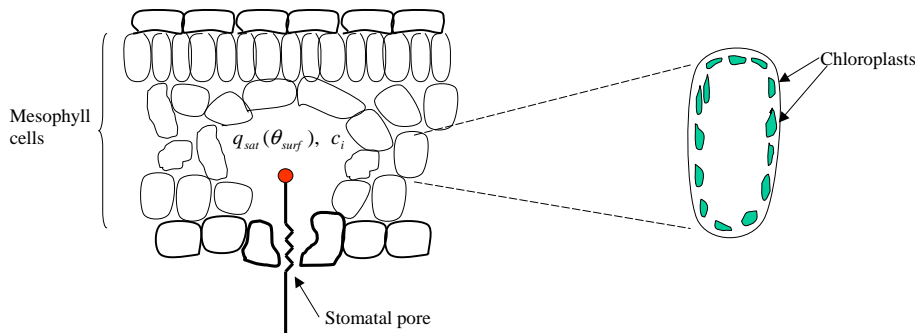
Figure 5. Photosynthesis takes place in the chloroplasts in the mesophyll cells. The degree of opening of the stomatal pores is reflected in the value of r_c.

Most micro-meteorological models for CO_2 uptake are based on the works by Farquhar, von Caemmerer and Berry (Farquhar *et al.*, 1980) and von Caemmerer and Farquhar (1981), who introduced a model for the photosynthetic uptake at the leaf scale. This model is henceforth referred to as the FCB model. They identify two functions limiting carboxylation; one concerns the conversion rate of radiation to chemical energy (which affects the re-generation of RuBP and is called the RuBP limiting rate) and the other reflects the amount of the enzyme Rubisco, which catalyzes the carboxylation, and acceptor molecules available for CO_2

present in the leaves (RuBP saturated rate). The most important parameters in the Farquhar model are J_{max} and $V_{c,max}$ which define the maximum conversion rate of radiation to chemical energy and the maximum carboxylation velocity at the RuBP saturated rate respectively.

At the leaf scale, CO_2 is lost to the atmosphere due to two processes: photorespiration and dark respiration. Photorespiration is the process where the carboxylation process is reversed and oxygen is fixed and carbon is released. Dark respiration is respiration that is not dependent on light, and it is a process whereby carbon is consumed to produce energy. It takes place in the mitochondria, which could be viewed as the power plants of the cells.

Ball, Woodrow and Berry (1987), analyzed stomatal conductance g_{st} and net leaf CO_2 assimilation $A_{n,leaf}$ and found a linear relationship between the two variables,

$$g_{st} = kA_{n,leaf} + m, \tag{8}$$

where k is a function of CO_2 partial pressure and relative humidity at the leaf surface and m is a constant. Their results were included in the work by Collatz *et al.* (1991), who formulated a complete model for simulation of gas and energy exchange of a leaf in free air. A slightly modified version of the Ball model was presented by Leuning (1995).

If the FCB photosynthesis model should be successfully implemented, $V_{c,max}$ and J_{max} need to be accurately assessed. Wullschleger (1993) presented a review for 109 species with values of $V_{c,max}$ and J_{max}. Several other studies have followed. Among these is a study by Wilson, Baldocchi and Hanson (2000), which in addition investigated the effect of leaf age on the parameter values.

From leaf to canopy

The linear relationship between stomatal conductance and net leaf photosynthesis (Eq 8) allows for a simple upscaling to the canopy level (Sellers *et al.*, 1992):

$$g_c = KA_n + mPAI, \tag{9}$$

where K is the canopy level counterpart of k in Eq 8, A_n is the canopy carbon dioxide uptake and it is assumed that m is the same for all leaves (and identical to the parameter in Eq 8). In order to assess A_n with the FCB model, assumptions on connections between internal leaf properties such as $V_{c,max}$ and J_{max} and the micro-environment of the leaves are necessary.

Light, temperature and humidity all vary as a function of depth in the canopy, but mean temperature and humidity variations can be considered smooth compared to the light extinction, which is exponential as a function of cumulative plant area. Since light is also limiting the photosynthetic uptake, there is a strong coupling between light profiles and carbon uptake. The upscaling is further complicated by the fact that photosynthetic response to light is a non-linear function.

For single-layer models, a common approach is to assume that maximum leaf photosynthesis capacity per leaf area and radiation profiles coincide as a function of cumulative plant area index (Sellers *et al.*, 1992). This assumption is called the acclimation hypothesis. Sellers *et al.* argue for the acclimation hypothesis using theory of economy and claim that the optimal canopy is fully acclimated. Since their conclusion leads to an analytical solution of canopy photosynthesis, the hypothesis is very attractive to modelers. For micro-meteorological modelling, the requirement for leaf measurements is reduced to the leaves in the top of the canopy. Later research has shown that canopies can not be considered fully acclimated but rather partially acclimated, *i.e.* that both maximum photosynthesis per leaf area and light decay exponentially in the canopy, but with different decay constants (Meir *et al.*, 2002).

The non-linear response of assimilation to light has been recognized since the 1970s, but lately stressed in the work by for example de Pury and Farquhar (1997). Many modelers have accordingly separated their radiation schemes into sun-lit and shaded leaves parts of the canopy when assessing canopy photosynthesis.

Other approaches

The work and theory summarized in the two previous sections reflect the main direction of the SVAT modelling field over the last decade. Out of the six models mentioned in the introduction, four use some variation of the above parametrizations. There are however other approaches. The SPA model by Williams *et al.* (1996) uses a formulation for leaf stomatal resistance which includes the water potential difference between soil and leaves. Hari *et al.* (1986) introduced a formulation for leaf conductance based on an optimality approach, where the gas exchange of the leaf is considered optimal when maximum amounts of carbohydrates are produced per unit of water vapor lost under prevailing environmental conditions. A parameter which could be considered the "cost of water" is introduced. Mäkelä, Berninger and Hari (1996) show that the cost of water is connected with the local precipitation frequency.

One of the advantages with the approaches of Williams *et al.* and Hari *et al.* compared to the Ball/Leuning model described above, is that their formulations of stomatal conductance do not depend on photosynthesis. Thereby a separation between the diffusion into the stomata and the internal leaf biochemical processes is possible. Both models also use a significantly simpler photosynthesis parametrization compared to the FCB model.

A third line of photosynthesis modelling for SVAT applications which has been widely used, is that introduced by Goudriaan (1985) and Jacobs (1994). They use a parametrization of the mesophyll resistance, which describes the process of diffusion of CO_2 from the stomata to the carboxylation site, hence extending the CO_2 pathway with an additional resistance.

Canopy scale respiration

For agricultural and forest production modelers, photosynthesis models provide an excellent tool to predict yield. From a climatological point of view, however, it is the net ecosystem exchange (NEE) which is of interest since it forms a basis for the calculation of terrestrial CO_2 sink strengths. The NEE reflects the ecosystem balance between assimilation and respiration, *i.e.*,

$$NEE = A_n - R_{soil} - R_{wt}, \qquad (10)$$

where A_n is the net uptake by the leaves in the canopy. Soil respiration (R_{soil}) and above ground woody tissue respiration (R_{wt}) signify the consumption of the photosynthesis products to gain energy. Soil respiration can be further divided into two components, root respiration (or autotrophic respiration) and microbial respiration (heterotrophic respiration), which may respond differently to environmental conditions. Respiration is commonly modelled with an exponential temperature response function. However, respiration is also dependent on soil water availability (Valentini *et al.*, 2000) and hence connected to productivity (Janssens *et al.*, 2001).

For R_{wt}, there is evidence of difference in the temperature response when comparing stems to branches (Damesin *et al*, 2002, Ceschia *et al*, 2002), which complicates upscaling to stand level. A second complicating factor is that daytime R_{wt} should be seen as a balance between respiration and photosynthesis since branches contain chlorophyll. The maximum re-fixation of carbon dioxide through the bark

has for small beech twigs been estimated to two thirds of the purely temperature dependent respiration (Damesin, 2003). For annual estimates, Meir and Grace (2002) found that R_{wt} could be expressed as a linear function of PAI and gross photosynthesis, but it is unfortunately not straightforward to scale this result down to smaller time periods.

3   Introduction to the Sorø site

In this section, an overview of the measurement site and general site characteristics is given. Results which form a background for the analysis presented in the papers are also shown.

The Sorø measurement station (55°29.19'N, 11°38.77'E) in Lille Bøgeskov was setup June 1st 1996 as a member of the EUROFLUX network and is still operational. The forest consists of approximately 85 year old beech trees, but has patches of coniferous trees. The beech trees are about 25m in height, have an average tree diameter of 40 cm and the stand density is 200-300 stem ha^{-1}. The soil is a mollisol with sandy loam in the top 20cm blending into a deeper layer with more clay (Østergaard, 2000). Instruments are mounted either on the 57m
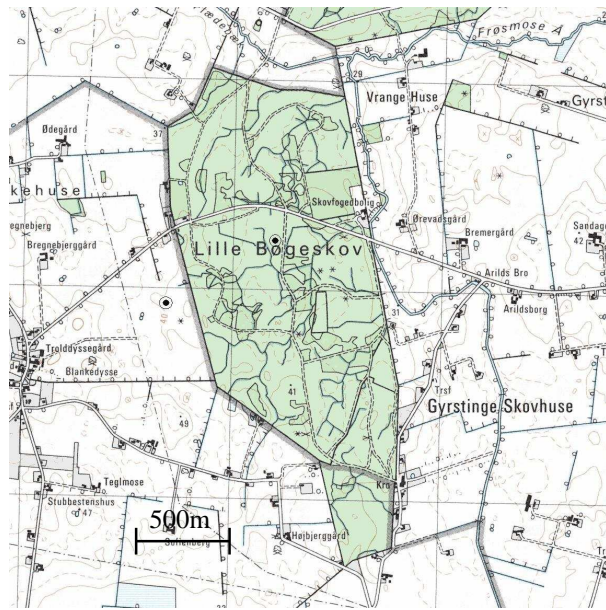

Figure 6. Map of the Sorø measurement site. The dark circles indicate positions of measurement masts. This thesis is only concerned with data from the mast in the forest.

high mast or the 25m high scaffold tower next to the mast. The forest extends 2km in the north-south direction and 1km in the east-west direction (Figure 6) and the mast is located approximately in the middle of the forest. The predominant wind direction is from the West-Southwest. North of the forest, there is but a small corridor separating Lille Bøgeskov from a considerably larger forest (Store Bøgeskov), which increases the effective fetch in the northern direction. The eddy-covariance measurements are made at 43m height, and consist of a closed path LiCor gas analyzer (LI-6262, LI-COR Inc., Lincoln, NE., USA) and a sonic anemometer (SOLENT, 1012 R2, Gill Instruments Ltd., Lymington, UK). Eddy

covariance measurements are recorded at 10Hz. Mean values of eddy-covariance measurements and meteorological measurements are calculated and stored every half hour. Instrumentation and data processing are described in detail in Pilegaard *et al.* (2001) and Pilegaard *et al.* (2003).

3.1 Site characteristics and a meteorological overview

The main focus of the flux station is to measure the carbon dioxide flux and assess the carbon budget of the forest. Figure 7 shows the cumulative carbon uptake as a function of time for seven growing seasons. If the growing season is defined as the time where the forest is a net sink for carbon, the length of the growing season ranges between 140 (in 1998 and 1999) and 160 days (in 2002). The onset of the growing season lies between day 120 and 125 for all years, whereas the time defining the end of the growing season shows greater variability (day 260-285). Similarly, the rate of the carbon uptake was comparatively uniform in the first few weeks of the summer for all years and show greater variability later in the summers.
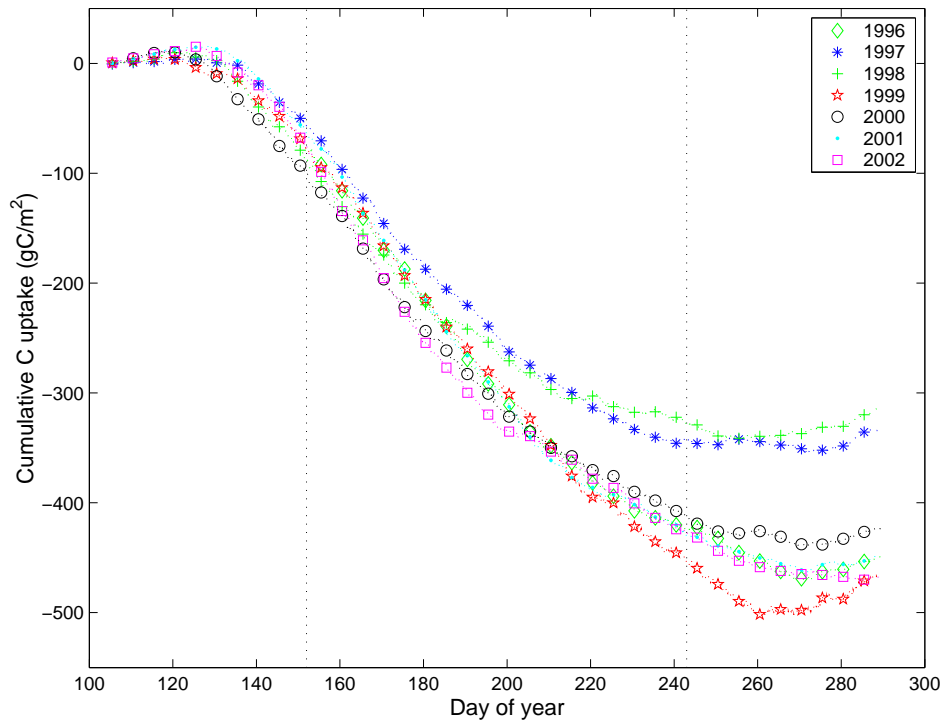

Figure 7. Cumulative carbon uptake for 7 summers of measurement.

One of the key parameters in canopy photosynthesis modelling is PAI. Figure 8 (upper graph) shows the seasonal variation of PAI. The variation in PAI is calculated using the relationship $I = I_0 e^{-k \cdot PAI}$, where I_0 is incoming radiation, I is below canopy radiation and k is a function of solar elevation angle, describing radiation extinction in the canopy. Calibration for the PAI calculation was made with an explicit measurement of PAI (PCA 2000, Li-Cor, Lincoln, NE, USA). Measurements of photosynthetic active radiation, PAR, were taken above and below the canopy with quantum sensors (LI-190SA, Li-Cor). The method and measurements used for the calculation is described in detail in Paper III. The mean value of the PAI estimates shows little variation ($\approx 5.0 m^2/m^2$) between

June 1st and September 1st. These dates are marked with the dotted lines in Figure 8).

Albedo is an important parameter for calculating the energy balance of the forest. The albedo is measured with an albedometer (CM14, Kipp & Zonen, BV, Delft, the Netherlands) at 30m height. The midday value of the albedo is around 0.17 around June 1st and drops to 0.14 around September 1st as the leaves darken (the diurnal variation not shown). These values are slightly higher than presented by Dolman (2003) for the same site, but agree well with the estimates in Monteith and Unsworth, 1990), who predict 0.18 for deciduous woodland.
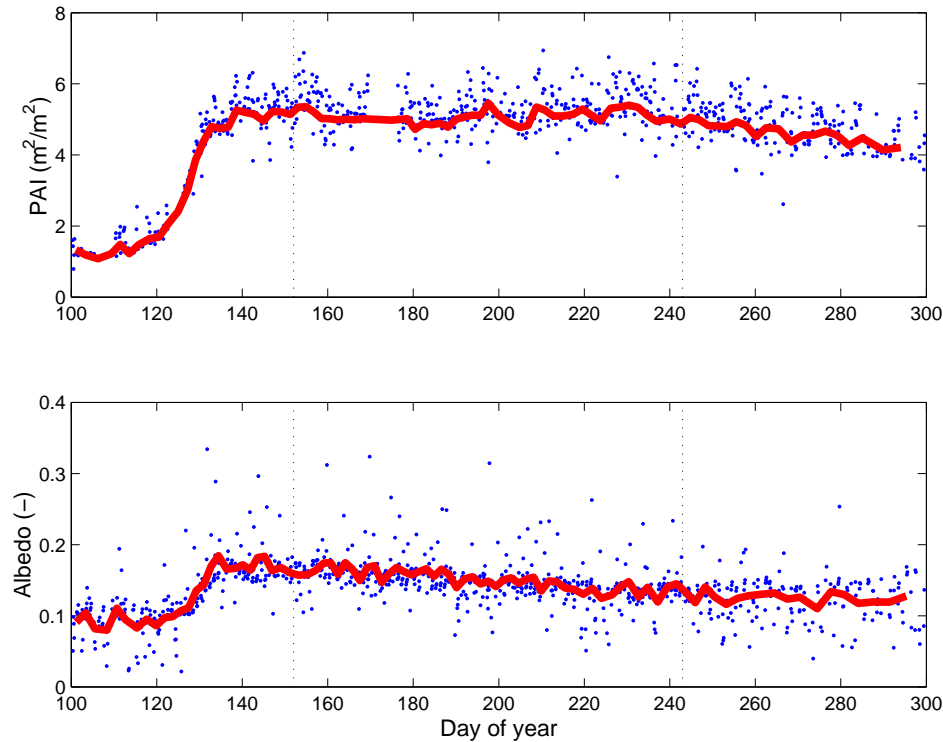
Figure 8. Seasonal variation in plant area index (PAI) and albedo in the summer of 2001. Albedo is maximal at the beginning of the summer, but decreases in the course of the summer as the leaves darken, whereas PAI is relatively constant over the summer. Vertical dotted lines correspond to June and September 1st.

Meteorological data from seven summers (between June 1st and September 1st) of measurements are summed up in Table 1 and Figure 10. Table 1 shows monthly precipitation, mean monthly temperature and data coverage. Mean summer temperatures varied between 14.6°C to 18.3°C. Mean summer precipitation showed greater variability, but is more uncertain since for most months, data coverage is less than 100%. Another indication of soil dryness is soil water content, which was measured every half hour with two (a and b) Time Domain Reflectometry instruments from 0-16cm depth starting in August 1996. Since the spatial variability in the top soil layer has shown to be relatively great due to influence from stem flow and so called drip points (Ladekarl, 2001), the half-hourly measurements were compared with an ensemble mean from 12-18 samples of daily measurements taken over greater depths. The result is shown in Figure 9. The b measurement is in reasonably close agreement with the 0-100cm measurement and will be used in further analysis.

Table 1. Monthly mean temperature at 37m height and cumulative precipitation.

		June	July	August	summer mean
1996	Precipitation (mm)	14.6	19.2	46.0	26.6
	$\theta_{37m}(^\circ C)$	14.4	15.5	18.1	16.0
	Coverage (%)	76	89	98	-
1997	Precipitation (mm)	14.2	23.2	34.6	24.0
	$\theta_{37m}(^\circ C)$	15.2	18.2	21.4	18.3
	Coverage (%)	68	61	89	-
1998	Precipitation (mm)	63.6	76.8	63.0	67.8
	$\theta_{37m}(^\circ C)$	14.4	14.5	14.8	14.6
	Coverage (%)	100	87	88	-
1999	Precipitation (mm)	105.2	11.6	140.0	85.6
	$\theta_{37m}(^\circ C)$	13.9	18.3	16.9	16.4
	Coverage (%)	100	62	97	-
2000	Precipitation (mm)	51.4	35.8	31.0	39.4
	$\theta_{37m}(^\circ C)$	13.9	15.1	15.5	14.8
	Coverage (%)	99	100	100	-
2001	Precipitation (mm)	46.6	41.8	146.8	78.4
	$\theta_{37m}(^\circ C)$	13.0	17.8	16.9	15.9
	Coverage (%)	99	95	95	-
2002	Precipitation (mm)	70.0	127.8	97.6	98.5
	$\theta_{37m}(^\circ C)$	15.4	17.5	20.7	17.9
	Coverage (%)	77	100	95	-

Soil moisture was converted to a wetness index ranging from 0 to 1 by using

$$W = \frac{SH - SH_{min}}{SH_{max} - SH_{min}}, \tag{11}$$

where SH denotes measured soil humidity and subscript max and min correspond to the measured maximum and minimum value. The minimum value was recorded in August 1997, where a soil water content of 7.8% was measured. The maximum reading is around 32% (several occasions). The result of applying Eq 11 to all soil humidity data is shown in Figure 10. The years 2000-2002 all contain a dry period with measurements down to or below $W \approx 0.15$, whereas 1998 and 1999 were relatively wet.

Qualitatively, it is relatively straightforward to couple mean meteorological data as presented in Table 1 and Figure 10 to carbon uptake. For example, the three years with the smallest uptake between June 1st and September 1st (1997, 1998 and 2000, Figure 7), correspond to two unusually dry summers (1997 and 2000) and one unusually cold summer (1998). An additional reason for the relatively low uptake in 2000 may be a lower plant area index, which was the result of a severe storm in December 1999.

3.2 Campaign measurements

Understorey eddy covariance measurements

During a considerable part of the seven-year time series from the Sorø site, complementary eddy covariance measurements in the trunk space (4m height) were taken with a similar setup as the above canopy eddy covariance measurements. Results from the first of these campaigns, which took place during the first half of July 1999, is shown in Figure 11. The data are presented in the form of ensem-
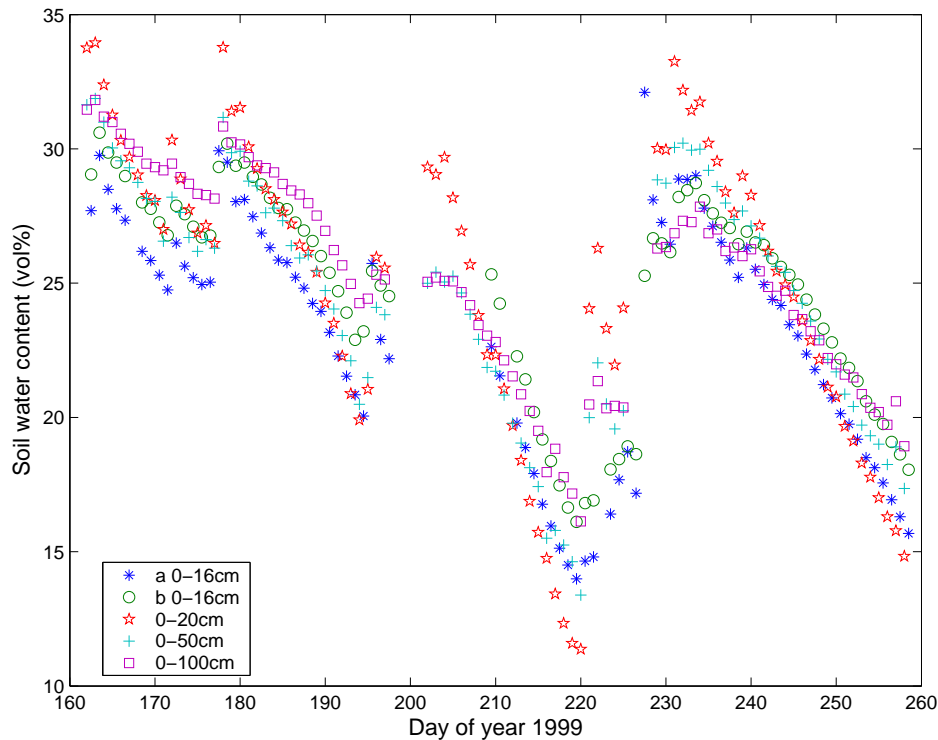
Figure 9. Comparison between half hourly 0-16cm measurements and daily measurements from Ladekarl (2001) taken at greater depth. Both half-hourly measurements (a and b) show good agreement with the measurements taken at greater depth. For the water availability of the tree roots, the 0-100cm measurement is most relevant. The b) measurement is closer to the 0-100cm daily measurement than the a) measurement.

ble days and the period of ensemble averaging was five subsequent days of sunny weather. Soil water was plentiful during the period ($W = 0.73$).

The mean daytime (between hours 7 and 17) contribution of trunk space fluxes to above canopy fluxes was calculated using the ensemble mean values. For the sensible heat flux, the day time trunk space flux was less than 2% of the above canopy flux, whereas for the latent heat flux it was approximately 7%. The understorey net assimilation, was -14% of the above canopy estimate. Friction velocity understorey values were approximately 13% of above canopy estimates. During night time, the mean value of all understorey signals is close to zero, except the carbon dioxide flux, which indicates significant soil respiration.

The eddy-covariance measurement taken at 43m gives a mean value of fluxes over a considerable area, whereas the 4m measurement gives a very local estimate. Ideally, trunk space measurements should be performed in additional locations in the forest to assess the spatial variability. However, at least concerning light availability, there is no reason to believe that the area around the mast is not representative, since it is located at a spot with vegetation structure typical of the forest ($\mathrm{PAI}_{forest} \approx \mathrm{PAI}_{mast}$).

Leaf measurements

Several leaf measurement campaigns concerned with aspects of photosynthesis have been undertaken in Sorø. Maximum carboxylation velocity, $V_{c,max}$, was measured on leaves from the top of the canopy in August 2001. Leaf cuvette mea-
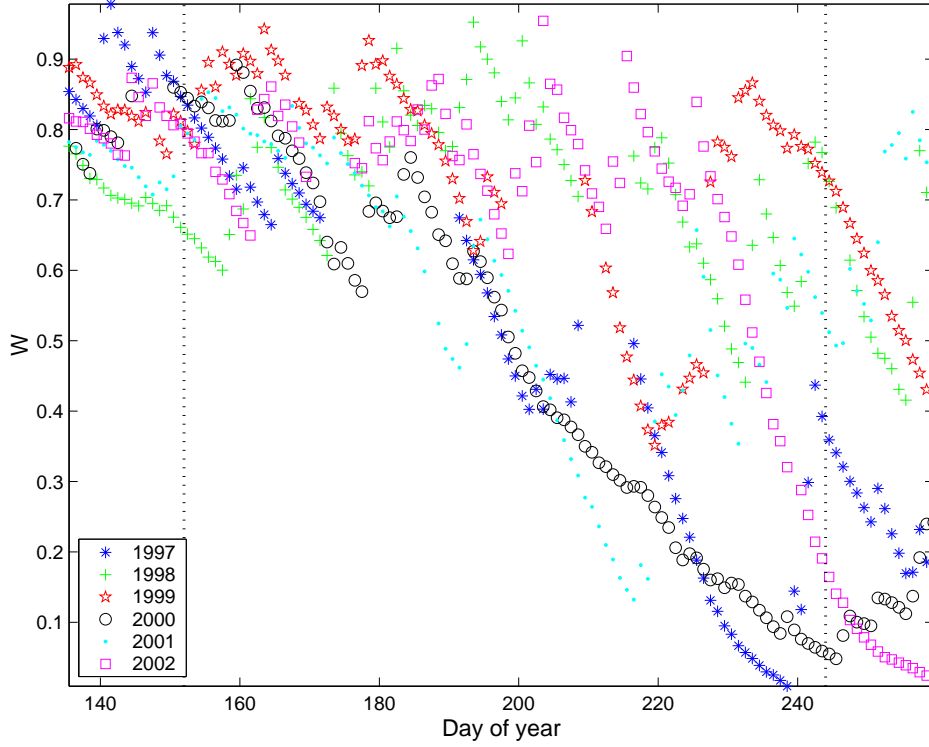
Figure 10. Soil wetness through six summers of measurements calculated from the soil water content measurement for 0-16cm. Vertical dotted bars correspond to June and September 1st. For a definition of W, see Eq 11.

surements were conducted weekly during two years (1999 and 2000) from May to October. These measurements were undertaken *in situ* in ambient conditions, whereas the $V_{c,max}$ measurements were taken on cut branches and performed in the lab. Ideally, $V_{c,max}$ should also be estimated *in situ*, but the equipment for performing the field measurements was not available. The $V_{c,max}$ measurement campaign represented an attempt to estimate this parameter for use in the FCB model.

For the $V_{c,max}$ measurements, top canopy branches were cut with a garden scissor mounted on a 2m long rod and re-cut under water before the transport to the laboratory. By using the long rod, suitable branches could easily be accessible. In the lab the branches were allowed to adapt and photosynthesize for an hour, after a second cutting under water. Measurements were conducted with a LI-6400 (Li-Cor, Inc. Lincoln, NE, USA). The measurements were performed in a climate-controlled room with $T = 25°C$, and a relative air humidity of 70%. Measurements were taken at PAR $= 1400\mu mol/(m^2 s)$. Preliminary analysis suggested that photosynthesis rates did not change significantly due to cutting and transport, but field measurements were scarce. A general problem was - both in the field and in the lab - that for some samples, it took a long time to reach equilibrium conditions at a given c_i. Between the second and the seventeenth of August 2001, measurements on 13 leaves from 13 different branches were taken. Measurements with $c_i \leq 150$ppm were used get an estimate of $V_{c,max}$, by minimizing the residuals between the data and the following function (von Caemmerer and Farquhar, 1981, Collatz, 1991)

$$A_n = V_{c,max}\frac{c_i - \Gamma_*}{c_i + K_c(1 + 0.2095/K_o)} - R_d \qquad (12)$$

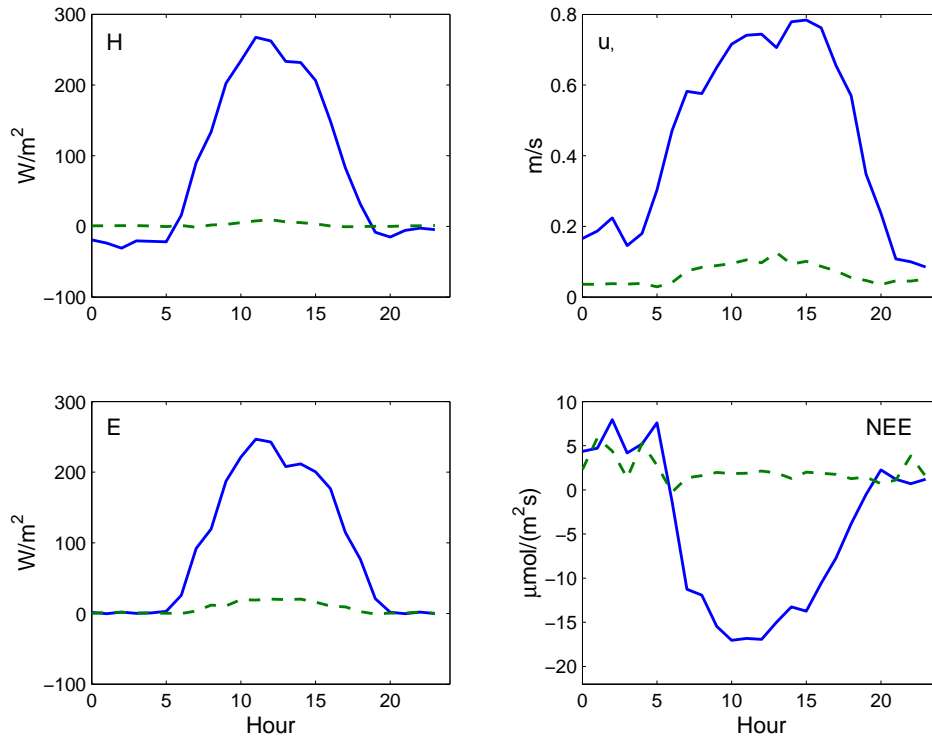where $\Gamma_* = 40.3$ppm (Collatz, 1991) represents the point at which the measured

Figure 11. Mean diurnal course of eddy covariance measurements taken at 43m (full line) and 4m (dashed line) for sensible heat (H), friction velocity (u_*), latent heat (E) and net carbon dioxide flux (NEE). Data from 5-7 subsequent sunny days were used for the calculation.

CO_2 flux equals R_d, and $K_c = 404$ and $K_o = 240$mmol/mol (von Caemmerer *et al.*, 1994) are the affinities for CO_2 and O_2 to Rubisco. The result of this analysis yielded $V_{c,max} = 33.4 \pm 17.9 \mu$mol/(m²s). Figure 12 shows the temporal variation of the $V_{c,max}$ measurements. There are several possible explanations to the large variability in the $V_{c,max}$ estimates. The natural variability between branches may be large and the branches may also have reacted differently to cutting, transportation and change of micro-climate.

The weekly measurements of leaf photosynthesis in 1999 and 2000 were taken at a variety of heights within the crown space at ambient conditions with an ADC LCA3, Portable photosynthesis and transpiration system (The analytical Development Co., Hoddesdon, UK) connected with a Parkinson Leaf Cuvette (Broad leaf) enclosing 6.25cm² leaf area. The duration of the measurement period was 1-2 minutes, and an ensemble of many measurements can be thought of as providing a "snapshot" of canopy dynamics. This data set has been used for analysis and comparison with canopy scale measurements (Paper III and IV). Figure 13 shows the net assimilation of all measurements taken in August 1999 with $|T_{leaf} - 27°| \leq 3°$C as a function of PAR. The temperature screening has been imposed to reduce scatter and $T_{leaf} \approx 27°$C corresponds to modelled temperature optimum in the canopy (Paper III, IV). In b), the corresponding light dependence of c_i is shown and c) finally shows $A_n(I)/c_i(I)$. The full line in a) and c) represents the best fit with a non-rectangular hyperbola (*e.g.* Marshall and Biscoe, 1980).
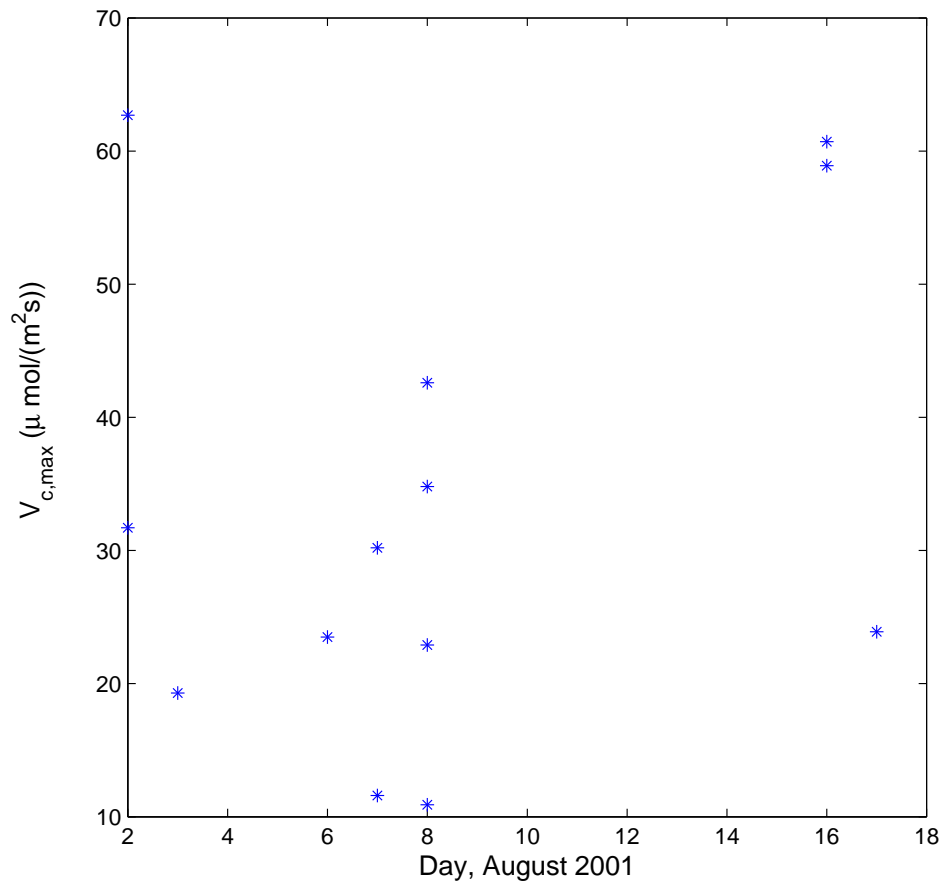
Figure 12. Measurements of 13 leaves for evaluation of $V_{c,max}$.

3.3   General conclusions concerning SVAT modelling at Sorø

- Fetch conditions at the Sorø site are sub-optimal and evaluation of this fetch limitation should be undertaken.

- During the seven years of measurements, the seasonal variability in soil water content and mean temperature was large, providing a good basis for SVAT modelling activities.

- Understorey contribution to above-canopy measurements was less than 8% for the sensible and latent heat flux, but considerably greater for the carbon dioxide flux (-13%). Hence modelling activities of understorey dynamics should focus on respiration.

- Measurements of leaf $V_{c,max}$ showed a lot of scatter. This could either be due to the method of measurement (on cut branches instead of *in situ*) measurement, or to a natural great variability between leaves. The field campaign of leaf level measurements at ambient conditions provide a less variable data set.
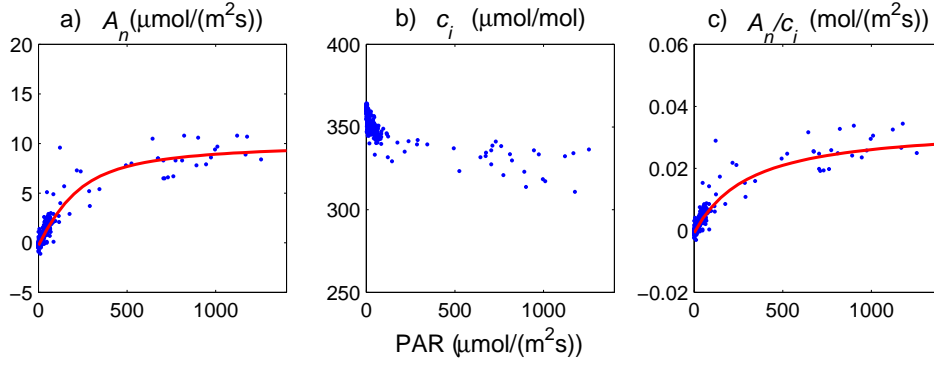
Figure 13. Ensemble of leaf measurements taken at ambient conditions, August 1999. Each point represent a different leaf. Measurements were taken at all depths is in the canopy.

4 SVAT modelling results from the Sorø site

Soil respiration was modelled using soil box data from 5-7 days in January 2000, April 2000, May 2000 and July 1999. The setup is described in Pilegaard *et al.*, 2001. This analysis was part of a comparison between above forest and trunk space eddy covariance measurements of the carbon dioxide flux. In order to find the seasonal variability and get a strong daily signal, data from each month were chosen from a period of constant and sunny meteorological conditions. For the
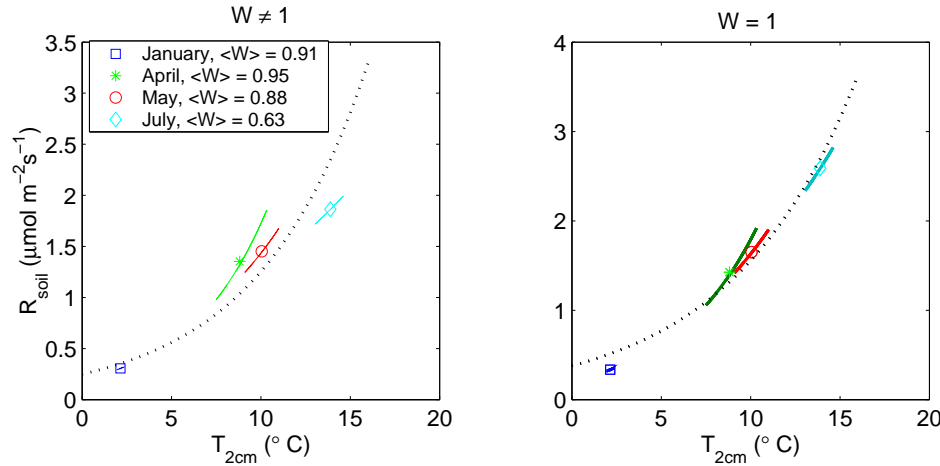
Figure 14. By normalizing with soil moisture (W), the temperature dependence show less scatter. The dotted line in the right graph corresponds Eq 14 with $Q_{10} = 6.0$ and $R_{T_{ref}} = 1.5 \mu mol/(m^2 s)$, where $T_{ref} = 10° C$. Corresponding values for the dotted line in the left graph (Eq 13) are $Q_{10} = 5.0$ $R_{T_{ref}} = 1.5 \mu mol/(m^2 s)$.

analysis of soil respiration, two models were chosen: a model which depended on temperature only,

$$R_{soil} = R_{T_{ref}} Q_{10}^{(T_{soil} - T_{ref})/10}, \tag{13}$$

where $R_{T_{ref}}$ signifies respiration at a reference temperature and Q_{10} the change of respiration at a 10° change of temperature, and a model which also took the

effect of soil water into account,

$$R_{soil} = R_{T_{ref}} Q_{10}^{(T_{soil} - T_{ref})/10} W, \qquad (14)$$

where W is defined in Eq 11. Implicit in this model is the assumption of maximum respiration at maximum soil moisture (W). The result of applying these models to data from the four periods and to all periods is shown in Figure 14. The dotted line represents the best fit to data from all periods. The scatter around this line decreases when the soil water effect is taken into account, *i.e.* the data are normalized to $W = 1$ (right graph). For clarity individual dots are excluded in the graphs and are replaced by lines which represent the diurnal change.

The aerodynamic resistance for heat (r_{ah}) and momentum (r_{am}) were estimated using detailed profile data from two field campaigns in the forest (see Paper II). The resistances were calculated from Eq 2, where the physical level of air properties in the canopy was associated with 21m. This height corresponds to the mean level of maximum temperature in the canopy. The result is shown in Figure 15 for unstable and stable atmospheric conditions. During unstable conditions and small values of u_*, there was a large discrepancy between r_{ah} and r_{am}, whereas the difference was smaller at greater values of u_* and during stable conditions.
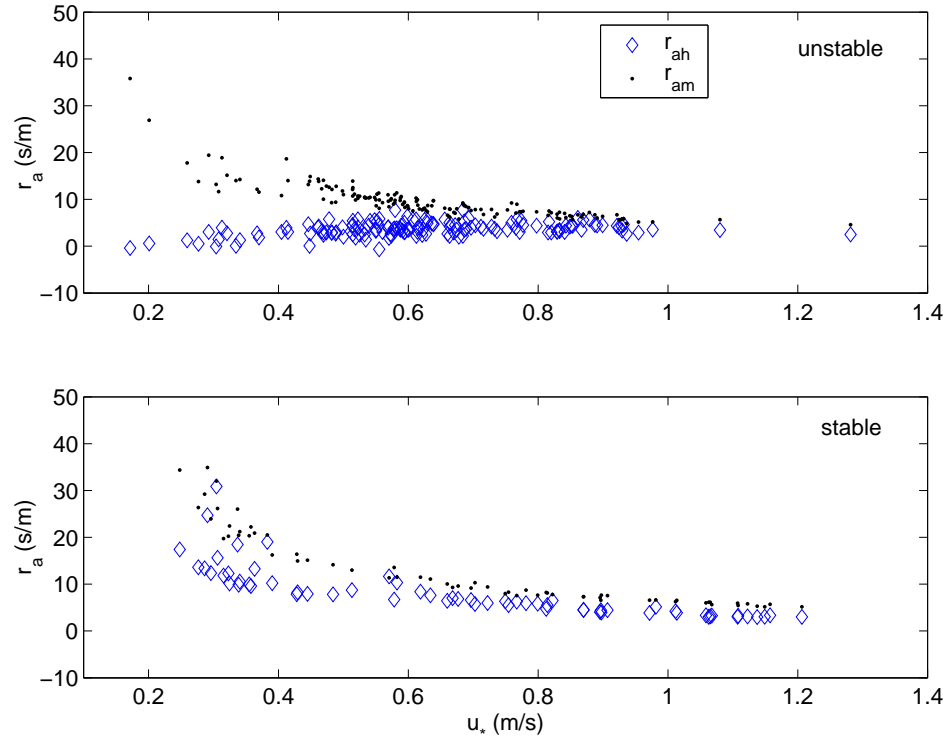

Figure 15. Estimates of aerodynamic resistance for momentum r_{am} and heat r_{ah}.

The different components in the carbon dioxide flux budget (Eq 10) were estimated from measurements and a model for woody tissue respiration. The resulting value of $A_{n,crown}$ was compared to an estimate based on leaf measurements taken at ambient conditions in the forest (see section 3.2.2). The agreement between the two estimates was good for June and July 1999 and for August 2000. The poor agreement for June and July 2000 can be explained by non-representative temperature conditions during the sampling periods (Paper III).
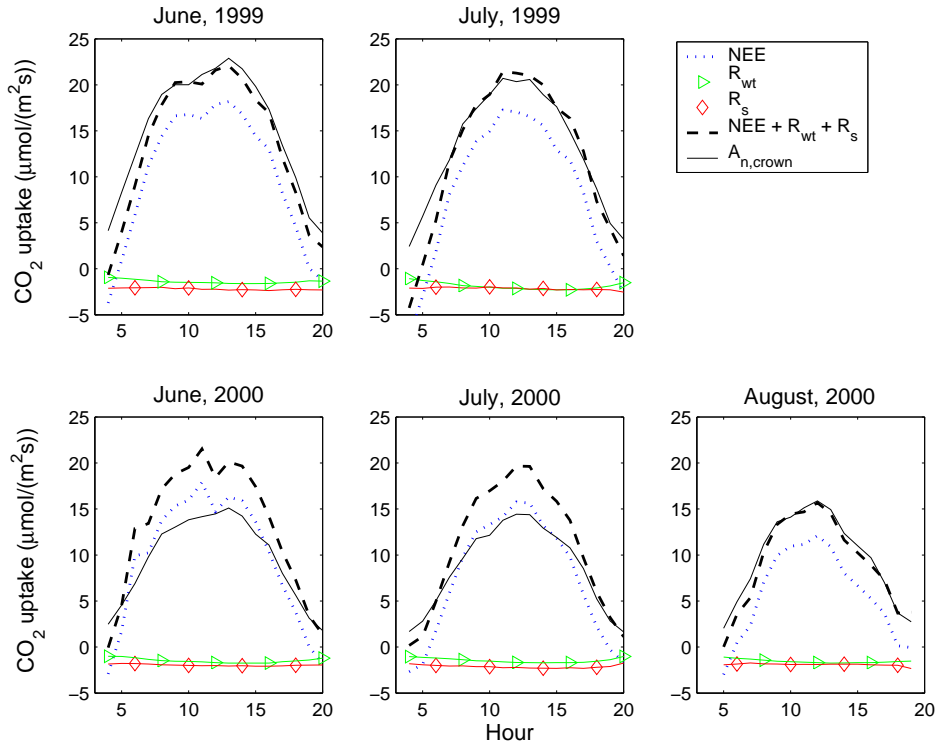
Figure 16. Comparison of scaled up estimates of crown photosynthesis $A_{n,crown}$ and estimates derived from on measured NEE, measured soil respiration R_{soil} and a model for woody tissue respiration.

5   Introduction to papers

Paper I: Internal equilibrium layer growth over forest

This work in this paper represents a continuation of a Master's thesis project. Preliminary data analysis and modelling was carried out as part of the MSc project, detailed analysis and manuscript writing were carried as part of the PhD project.

Ratios of friction velocity measurements taken at different heights are analyzed with the aim of assessing the growth of the internal boundary layer. Data come from measurement masts in two Danish beech forests of similar age and density. The results from one of the forests (Coreselitze Østerskov) were used to derive a model for the growth of the internal equilibrium layer, which is the lowermost part of the internal boundary layer where the flow is in equilibrium with the underlying surface. From the other forest (which is the Sorø site), the measurement results were inconclusive mainly due to a difficulty in assessing the effective fetch length from the main wind directions during the time of the experiment. The derived model was applied to the Sorø site. For a fetch of 500m and a surface roughness of 1.6m (Sorø parameters), the internal equilibrium layer height was estimated to 14m above the displacement height ($\approx$ 19m) for neutral atmospheric conditions. This result implies influence on the eddy covariance measurements from upwind fields for the shorter fetches at the Sorø site.

Paper II: Flux-profile relationships over a fetch limited beech forest

This paper had two objectives. The first was to better understand the influence of internal boundary layers on the measurements in Sorø, and is in this sense a continuation of Paper I. The effects of the roughness sublayer is also investigated. The second objective was to evaluate the aerodynamic and viscous sublayer resistances at the site.

The results of the analysis indicate that a) flux-profile relationship at the Sorø site show typical roughness sublayer features and as well as trends indicating internal boundary layer influence and b) that there is a simple way of parametrizing r_a and r_b over the forest.

Paper III: Scaling carbon dioxide uptake from leaf to crown in a temperate beech forest

In this paper, ensembles of cuvette leaf measurements were analyzed on a monthly basis and compared to eddy-covariance measurements of net ecosystem exchange taken above the canopy. The canopy level respiratory components were modelled separately, so as to allow for comparison. A radiation transfer scheme was derived using canopy profile PAR measurements and cumulative leaf area index measurements.

The comparison between the scaled up crown photosynthesis (A_{crown}) and the estimate based on the eddy covariance measurements with subtraction of respiration was good. It suggests high levels of respiration from the woody tissue in the crown, which is in agreement with previous studies.

The method in the paper is different from the modelling framework based on the works of Farquhar *et al.*, 1980, in that the smallest scale included is the leaf scale. It is also different from many model papers, in that it builds on leaf measurements taken at ambient conditions (in contrast to the FCB approach, where the environment of the leaves is manipulated to give parameter estimates).

Paper IV: Canopy conductance of a temperate beech forest compared to the optimal stomatal control hypothesis

This paper builds on the work in Paper II and III. The formulations for aerodynamic and viscous boundary layer resistance were used to estimate mean canopy air and leaf temperature for a single layer model. The mean leaf and canopy air temperatures were together with canopy level water vapor fluxes used to estimate canopy conductance. A similar approach as in Paper III is used to estimate canopy photosynthesis capacity per internal CO_2 concentration. These results were used to calibrate and run a model for optimal stomatal conductance. The calibration yielded similar parameter values as for a model run for Scots pine (Hari and Mäkelä, 2003).

This paper is currently incomplete, since additional assessments of data quality are necessary. More specifically, there is a relatively large variation in estimated lag time for the water vapor signal from the closed path eddy-covariance system which needs to be further analyzed and the magnitude of the low-pass filtering of eddy-flux signals needs to be estimated.

A few additional aspects would also be good to discuss in the paper. The method for estimating canopy conductance values could be compared to the estimates from inverting the Penman-Monteith equation. Further, the analysis could incorporate

branch level estimates of the calibration parameter.

6   Perspectives and future work

6.1   Perspectives for further studies
- the Sorø site

The model results from paper IV were derived from data taken during the dry spell
in August, 1997. Extending the period of modelling to the whole seven years data
series would be interesting. Further the Hari *et al.* (1986) model should be applied
on the branch scale, using branch cuvette measurements, in order to examine to
what extent the main parameter of the model is scale independent.

The internal boundary layer influence on carbon dioxide flux data should be
investigated more thoroughly. An experiment with this purpose is planned for the
summer of 2004. Flux data should also be corrected for spectral losses due to
high pass and low pass filtering (see *e.g.* Massman and Lee, 2002). However, only
small corrections are expected because of the carefully designed setup and the
high measurement height.

In this thesis, the separation of light into its direct/diffuse components has
not been undertaken, since good results were achieved with a simpler approach.
However, since an increasing number of studies (see *e.g.* Law *et al.*, 2002 and Gu *et
al.*, 1999 and 2002) show the canopy scale significance of this separation, it would
be interesting to investigate its effect on the Sorø data sets. Measurements of the
diffuse and direct radiation components started in May 2003.

Results from this thesis could contribute to the field of wind engineering. With
the introduction of bigger wind mills, it has become cost-efficient to raise wind
mills near and in forested areas. Forests may be a sub-optimal location for wind
mills, but if forest wind mills are introduced, at least it should be done in the best
possible way.

This thesis may also contribute with ideas as how to assess carbon dioxide and
water vapor fluxes at a regional scale.

6.2   Perspectives for further studies
- SVAT modelling

While the increasing FLUXNET database makes it possible to investigate carbon
and water fluxes on the seasonal time scale (see Law *et al.*, 2002), currently most
micro-meteorological modelling to assess surface fluxes is performed with highly
detailed multi-layer models. In order to find the simpler solutions, it is necessary
to understand the details of the systems. When enough detail is found, the simple
seasonal scale studies and the multi-layer ecosystem models may make a new type
of modelling more attractive. This would involve shorter time scales than the
seasonal scale comparisons and less detail than the multi-layer models without
losing predictability and precision.

Concerning the difficult task of modelling the carbon dioxide flux, it would be
desirable to understand the connection between respiration and photosynthesis
on the ecosystem level. Despite all the details and different processes on different
scales within the ecosystem, experimental results (Janssens *et al.*, 2001) indicate
that the ecosystem may be modelled as one dynamic unit.

To meet modelling requirements from the climate change community, it will not
suffice to capture vegetation dynamics as they appear at present, but models also

need to be able to predict the deviations from an equilibrium state. In current models, deviations from the normal are often modelled with empirical correction functions. These may be site-dependent and hence difficult to generalize. A better tool is offered in the use of differential equations. In using differential equations, the state of the present is dependent on the state of the past. A differential equation can be applied on many timescales to assess both changes over longer period as well as the hourly scale.

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Abstract (max. 2000 characters)

The work in this thesis concerns data evaluation and soil-vegetation-atmosphere-transfer (SVAT) modelling of measurements taken in and above a temperate beech forest canopy.

The beech forest site is fetch limited and influence on forest mast measurements from upwind farmland was investigated. The influence was studied (1) by analyzing ratios of friction velocity taken at different heights in the mast as a function of fetch length and (2) by studying the flux-profile relationship of wind speed and momentum flux, and temperature and sensible heat flux, respectively. The results indicated that the forest site is influenced by the upwind conditions via internal boundary layers. The forest flux-profile relationships were interpreted in terms of aerodynamic resistances. Additional measurements yielded information on the viscous sublayer resistance for heat. Total atmospheric resistances for sensible heat and momentum were approximately equal.

Regarding the modelling of soil-vegetation-atmosphere interaction, the focus was on carbon dioxide exchange. A simple model was developed where leaf measurements taken at ambient conditions were used to construct a mean canopy light response curve, which was integrated to yield the carbon dioxide uptake into the tree crowns. In order to compare with the eddy-correlation measurements of net ecosystem exchange, models and measurements of the ecosystem respiration were included. Agreement between the eddy-correlation based estimate and the leaf-measurement based scheme was generally good.

Together with a simple model for the atmospheric resistances, temperature measurements and water vapor fluxes were analyzed to give estimates of mean canopy resistance. The derived estimates were compared to a canopy scale version of the optimal stomatal conductance hypothesis, which regards water lost via transpiration as a cost when assimilating carbon. An approach which calculates canopy photosynthesis analytically is also presented.

The work in this thesis represents an attempt to derive simple but accurate formulations for single-layer models of trace gas and heat exchange in forested areas.

Descriptors

Aerodynamic resistance, canopy reisitance, carbon dioxide, climate, flux, internal boundary layer, micro-meteorology, roughness sublayer, resistance network, stomata, turbulence, vegetation