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The HartX-Synthesis: An Experimental Approach to Water and Carbon Exchange of a Scots Pine Plantation

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With 5 Figures

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Summary

In May 1992 during the interdisciplinary measurement campaign HartX (Hartheim eXperiment), several independent estimates of stand water vapor flux were compared at a 12-m high Scots pine (*Pinus silvestris*) plantation on a flat fluvial terrace of the Rhine close to Freiburg, Germany. Weather during the HartX period was characterized by ten consecutive clear days with exceptionally high input of available energy for this time of year and with a slowly shifting diurnal pattern in atmospheric variables like vapor pressure deficit. Methods utilized to quantify components of stand water flux included porometry measurements on understory graminoid leaves and on pine needles and three different techniques for determining individual tree xylem sap flow. Micrometeorological methods included eddy covariance and eddy covariance energy balance techniques with six independent systems on two towers separated by 40 m. Additionally, Bowen ratio energy balance estimates of water flux were conducted and measurements of the gradients in water vapor, CO_2, and trace gases within and above the stand were carried out with an additional, portable 30 m high telescoping mast.

Biologically-based estimates of overstory transpiration were obtained by up-scaling tree sap flow rates to stand level via cumulative sapwood area. Tree transpiration contributed between 2.2 and 2.6 mm/day to ET for a tree leaf area index (LAI) of 2.8. The pine stand had an understory dominated by sedge and grass species with overall average LAI of 1.5. Mechanistic canopy gas exchange models that quantify both water vapor and CO_2 exchange were applied to both understory and tree needle ecosystem compartments. Thus, the transpiration by graminoid species was estimated at approximately 20% of total stand ET. The modelled estimates for understory contribution to stand water flux compared well with micrometeorologically-based determinations. Maximum carbon gain was estimated from the canopy models at approximately 425 mmol/(m^{2}day) for the tree needles and at 100 mmol/(m^{2}day) for the understory. Carbon gain was suggested by the modelling analysis to remain relatively constant during the HartX period, while water use efficiency in carbon fixation increased with decreasing vapor pressure deficit. Biologically- and micrometeorologically-based estimates of stand water flux showed good general agreement with variation of up to 20% that reflects both errors due to the inherent assumptions associated with different methods as well as natural spatial variability in fluxes. The various methods support a reliable estimate of average ET from this homogeneous canopy during HartX of about 2.6 mm/day (a maximum of about 3.1 mm/day) with an insignificant decreasing trend in correlation with decreasing vapor pressure deficit and possibly soil moisture.

Findings during HartX were embedded in local scale heterogeneity with greater roughness over the forest and much higher ET over the surrounding agricultural fields

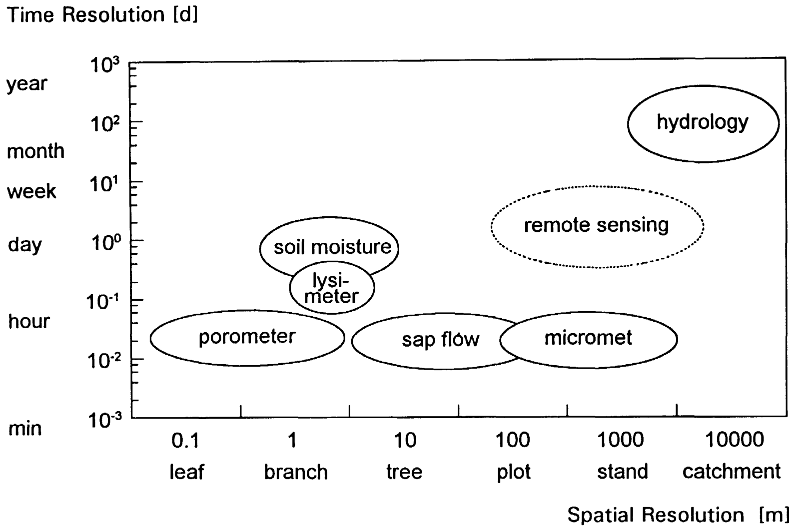

Fig. 1. Methods to estimate water flux between vegetation and the atmosphere and their typical resolution in time and space

which results in weak but clearly existant circulation patterns. A variety of measurements were continued after the HartX campaign. They allow us to extend our findings for six months with changing environmental conditions, including shortage of soil moisture. Hydrological estimates of soil water extractions and micrometeorological estimates of ET by the one-propeller eddy covariance (OPEC) system were in very good agreement, supporting the use of this robust eddy covariance energy balance technique for long-term monitoring.

1. Introduction

Biologically- ("Bottom-Up") and micrometeorologically-based ("Top-Down") methods were applied simultaneously at an ideal plantation site and for a limited period of time with high radiation input (Hartheim eXperiment, HartX, May 11 to May 22, 1992) to examine Scots pine (*Pinus silvestris*) forest gas exchange (see site descriptions in Jaeger and Kessler, 1995; Wüthrich, 1995, this issue). Characteristics that contribute to the "ideal" nature of the site are favorable fetch, relative structural homogeneity, and location on the flat fluvial terrace of the Rhine River, south of Freiburg, Germany. Additionally, long-term documentation of environmental conditions, soil water storage, and vegetation development exists for this permanent station (Kessler et al., 1988; Kessler and Jaeger, 1994). At this ideal site, we attempted to relate the detailed process information obtained with "Bottom-Up" methods to independent estimates from "Top-Down" techniques.

Measurements were conducted at several levels of spatial and temporal resolution (Fig. 1). The analysis draws these various measurements as well as model simulations together, in an effort to develop a comprehensive understanding from the following:

(i) the confidence limits for absolute values of water fluxes on a diurnal basis and the magnitude of errors associated with inherent assumptions of different methods and natural spatial variability in fluxes,
(ii) the limits on ET that are imposed by biological control mechanisms, and
(iii) the manner in which water and carbon dioxide fluxes respond on a short-term basis (minutes to hours) to changing environmental conditions, leading to shifts in water use efficiency with changing atmospheric ET demand.

The results of studies of this type will help us devise long-term strategies for continuous measurements of water and carbon dioxide fluxes at selected sites which are needed as anchor points to support regional and mesoscale water balance modelling efforts.

The weather during HartX was extremely favorable with ten consecutive clear days and with daily variability in the driving variables of water and carbon fluxes (Fig. 2) that might be visualized and planned for a laboratory experiment. The first part of HartX (May 11 to May 16) was characterized by increasing air temperature, increasing

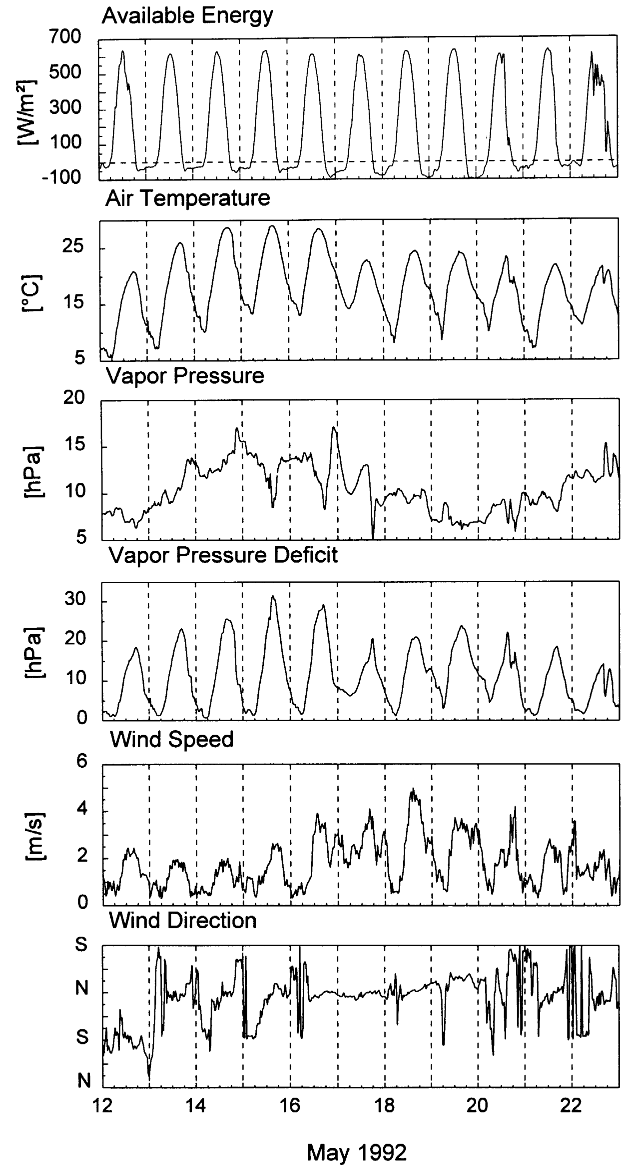

Fig. 2. Atmospheric characteristics (15 m above ground at the "large tower" of the Institute of Meteorology, University of Freiburg) over a Scots pine plantation (average height 12 m) near Hartheim/Germany during the extensive measurement campaign HartX in May 1992. Data shown include available energy (net radiation R_n – soil and canopy storage G; Vogt et al., 1995, this issue); other data are from Jaeger and Kessler (1995, this issue) and Vogt (1995)

vapor pressure deficit and low wind speed; the second part (starting in the afternoon of May 16 to May 22) showed lower air temperature, lower vapor pressure deficit and higher wind speed. In general, available energy and wind direction remained unchanged (see also Jaeger and Kessler, 1996 this issue). Detailed measurements made within and above the canopy on three towers separated by 20 to 60 m showed almost no vertical gradients in temperature, humidity and trace gases between the pine crown and soil surface (see Joss and Graber, 1996, this issue). This is attributed to the incomplete canopy closure of the plantation trees oriented in rows and strong daytime aerodynamic coupling.

2. From Leaf to Stand

2.1 Water Fluxes

The methods used by the HartX participants to evaluate water fluxes at several spatial scales are summarized in Table 1. They include weighing lysimetry, porometry, sap flow, determinations of soil water storage and hydrological balance, eddy covariance, and gradient methods like Bowen ratio energy balance. Aircraft and satellite remote sensing was used to examine stand heterogeneity. Typical time resolution for the measurement of water fluxes during HartX was 30 min. Several studies were extended after the HartX period in May 1992 (Table 1), permitting a solid integration with long-term energy and water balance records that have been kept at the Hartheim plantation (Kessler et al., 1988).

2.1.1 Understory Fluxes

Plot scale gas exchange (leaf, branch, and whole plant) and soil water balance studies (Wedler et al., 1996a, b, this issue; Siegwolf, personal communication) were utilized to estimate understory contributions to stand evapotranspiration. The up-scaled information was combined with studies carried out at the tree level (Granier et al., 1996; Köstner et al., 1996; both this issue) to quantify water flux partitioning (Figs. 3 and 5). Porometer measurements on the dominant graminoid species of the understory were supplemented with small lysimeter estimates for bare soil patches and for the major understory communities. An aggregation scheme based on the spatial coverage by vegetation patches and the SVAT model GASFLUX (Tenhunen et al., 1994) were utilized by Wedler (1996a, b; this issue) to spatially integrate water and carbon fluxes of the understory. The aggregated understory evapotranspiration was about 20% of total ET and in good agreement with direct measurements by eddy covariance (Bernhofer et al., 1996, this issue).

Physiological differentiation was found among the major graminoid species, with *Carex alba* utilizing water in a very conservative manner as compared to *Carex flacca* and *Brachypodium pinnatum.* Thus, the understory communities present a mosaic with low density (low LAI) patches exhibiting high leaf nitrogen content and high leaf-area-based flux rates (*Carex flacca* and *Brachypodium pinnatum*) and very extensive, dense *Carex alba* patches with low leaf nitrogen content and low leaf-area-based flux rates. The observations suggest a dynamic competition for light and space between these plant types that is probably sensitive to long-term water availability and which deserves further study.

2.1.2 Tree Overstory Fluxes

Despite the regularity in plantation planting and thinning, considerable variation in tree size, tree density and soil conditions occurs at small scales (Granier et al., 1996; Sturm et al., 1996; both this issue). Cumulative sapwood area of the stand which was used to extrapolate from tree to stand transpiration rates varied +/−15% within 5 plots of ca. 600 m^2 (Granier et al., 1996, this issue). A minimum of 10 trees was necessary to approximate the daily sap flow averages for all trees measured (24 trees) within +/−8% (Köstner et al., 1996, this issue). Variation in xylem sap flux density of individual trees was relatively high, but remained within the same range for all three xylem sap flow systems used. The dependency of sap flow rate on depth of sensor placement in the trunk remains a factor that may affect estimates of ET obtained with these methods, at least in the case of pines (Granier et al., 1996, this issue).

Although soil water conditions appeared sufficient to support a similar level to tree transpiration during the entire HartX period, a continuous depletion of soil water occurred (HartX began with soil water storage of 40% of available water and ended with approximately 25%). Soil water content near the end of the HartX campaign was close to the soil water content which induces stomatal closure in *Pinus silvestris* at this site (Sturm et al., 1996, this issue). However, the observed soil water depletion did not appear to

Table 1. *Methodologies Used During the HartX Measurement Campaign to Evaluate Water and Carbon Exchange Above a Scots Pine Plantation near Hartheim/Germany in May 1992 and Long-term Follow-up Studies Through 1994* (for individual contributions refer to other papers of this special issue)

Method	Study Object	Applied to Understory or Trees	Data Record (May 1995)	Exchange of H_2O or CO_2	Extended through 1994	Authors (all this issue)
Weighing lysimetry	soil sample	U/-	13 to 19	H_2O	---	Wedler et al., 1996b
Soil moisture	patch	U/T	11 to 22	H_2O	X	Sturm et al., 1996
Porometry	Leaf/twig	U/T	17 to 21	H_2O/CO_2	---	Siegwolf, pers. comm.; Wedler et al., 1996a,b
Sap flow	tree	-/T	12 to 22	H_2O	X	Granier et al., 1996; Köstner et al., 1996
Micrometeorology	canopy	U/T	12 to 22	H_2O	---	Bernhofer et al., 1996; Gay et al., 1996a, b; Jaeger and Kessler, 1996; Joss und Graber, 1996; Vogt et al., 1996; Wicke and Bernhofer, 1996
Hydrology*)	plantation	U/T	---	H_2O	X	Gay et al., 1996b; Jaeger and Kessler, 1996
Remote Sensing	patch to plantation	-/T	22	**	---	Wüthrich, 1996

* no runoff, constant soil moisture (evapotranspiration equals precipitation)
** applied only for the examination of heterogeneity

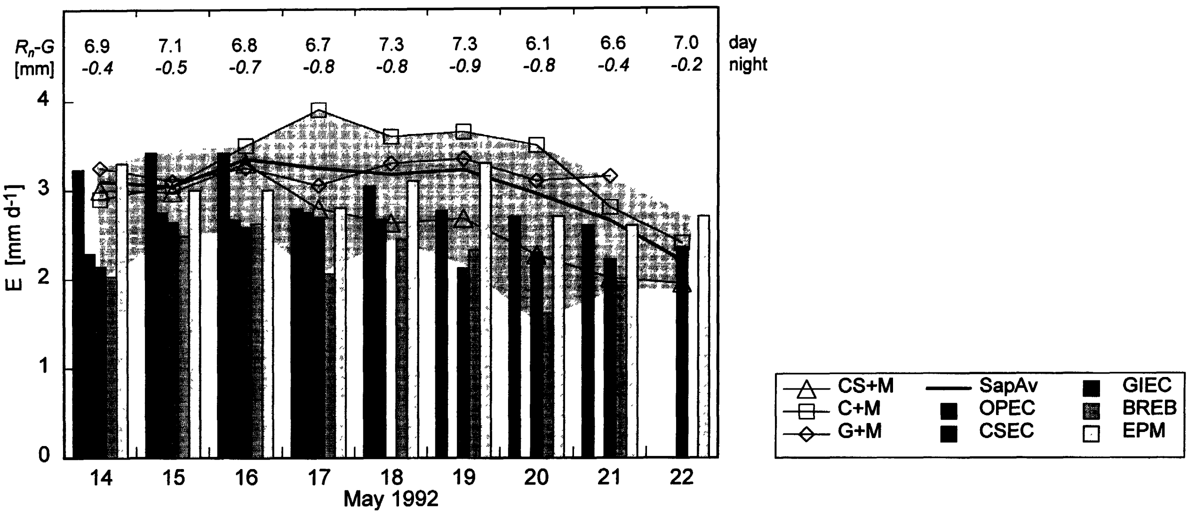

Fig. 3. Daily sums of ET by various methods applied at a Scots pine plantation near Hartheim/Germany in May 1992. "Bottom-Up" estimates include three sap-flow methods (CS = Cermák-Schulze, G = Granier, C = Cermák; as desribed in Köstner, 1995, this issue) depicted as the sum of tree and modelled understory contribution (" + M") according to Wedler et al. (1995, this issue); also shown the average "Bottom-Up" estimate SapAv. "Top-Down" estimates include OPEC (One-propeller Eddy Covariance of Blanford and Gay, 1992), CSEC (Campbell Scientific One Dimensional Sonic Eddy Covariance), GIEC (Gill Instruments Sonic Eddy Covariance) and BREB (Bowen Ratio Energy Balance) as described in Gay et al. (1995a, this issue) and Vogt (1995). EPM is modelled ET according to Penman-Monteith utilizing a parameterization scheme of Wicke (1988) developed for the Hartheim pine plantation. Also shown water equivalent of available energy $R_n - G$ in mm/day, separated into day (solar radiation > 0) and night periods. The shadow band highlights the span between lowest and highest daily estimate of the various methods

significantly reduce ET as judged from either "Top-Down" or "Bottom-Up" methodologies (Fig. 3), since the trends in ETduring HartX were easily explained in terms of changes in atmospheric driving variables like vapor pressure deficit (Fig. 2).

2.1.3 Stand (Canopy)

Stand level ET was assessed by up-scaling leaf-level measurements with simulation models, but also directly via "Top-Down" methods. Eddy covariance (EC) is the method of choice for "Top-Down" estimates of water fluxes above rough canopies like forests. Although applied simultaneously during HartX, gradient methods are limited by a resolution requirement that is operationally hard to meet (Wicke and Bernhofer, 1995, this issue). Separate EC measurements of sensible and latent fluxes allow an independent comparison with available energy. However, this "ultimate proof" of flux rates through energy balance closure (Baldocchi, 1994) relies not only on well-calibrated net radiation measurements but also on sophisticated correction schemes.

During HartX, a variety of net radiometers were used and carefully examined for calibration and instrument errors (Vogt et al., 1995, this issue). None of the four independently calibrated radiometers showed a systematic bias and after separate calibration factors for shortwave and longwave radiation were applied, all net radiometers agreed within +/−5%. The magnitude of soil and "canopy" energy storage terms was also established with two different methods. Nevertheless, a sizable discrepancy occurred during HartX with respect to energy balance closure (difference between the sum of the EC measured turbulent fluxes and available energy) of 5 to 25% on a daily basis. Detailed analysis of energy balance closure with special emphasis on phenomena during night-time is given in Vogt (1995).

Reasons for failing to achieve closure include primarily non-turbulent transport in "up- and down-drafts" that occur under convective conditions violating theoretical assumptions for EC (mean vertical wind $w = 0$), but also instrumental shortcomings. However, for purposes of water flux evaluation the ECEB (Eddy Covariance Energy Balance) technique showed reliable results (Gay et al. 1995a, this issue). Gay et al. (1995a, this issue) developed a correction scheme to take care of the "phantom dew" detected by any ECEB system under stable night-time conditions. ECEB uses available energy and EC measurements of sensible heat flux to calculate ET as a residual. Thus, it assumes that the failure in closure lies primarily in the EC estimate of the turbulent latent flux. This assumption is supported by good similarity in the various EC estimates of sensible heat flux on two towers separated by 40 m. Particularly the robust one-propeller system (OPEC) of Blanford and Gay (1992) provided identical results to a one dimensional sonic EC system on the same tower. The failure in achieving energy budget closure according to this interpretation is attributed to a bias in the EC method (which assumes instantaneous measurements and excludes non-turbulent fluxes) which more critically influences the estimates of latent flux with current instrumentation.

Gradient methods to evaluate the energy balance components were applied simultaneously at the Scots pine plantation and at a grassy site in the vicinity (Gay et al., 1995a, this issue; Vogt, 1995; Wicke and Bernhofer, 1995, this issue). These data exhibited greater scatter and less reliability over the rough surface of the plantation than did EC, though a sophisticated exchanging psychrometer system was used. Therefore, they are not recommended for operational use above forests and should be replaced by EC measurements.

2.1.4 Agreement of "Bottom-Up" and "Top-Down" Methods

Since day-to-day variation in environmental conditions was low (Fig. 2), the day time water equivalent of available energy changed only from 6.1 mm to 7.3 mm (Fig. 3). The overall pattern established with micrometeorological methods as well as the average of the three sap-flow methods combined with modelled understory fluxes show an insignificant trend towards lower ET at the end of HartX. The various methods support a reliable estimate of average ET from this homogeneous canopy during HartX of about 2.6 mm/day (a maximum of about 3.1 mm/day). For comparison an independently calibrated Penman-Monteith estimate of actual ET according to Stewart (1988) as adopted by Wicke (1988) is added. This estimate also agrees well with measured values, stressing the applicability of simple yet carefully adjusted approaches to forest ET for certain purposes. Despite the observed variability in tree sap flow rate, in tree density, and in potential soil water storage, scaled-up canopy transpiration of all 24 trees sampled plus evapotranspiration from the understory agreed with micrometeorological estimates within 2 to 20% (Fig. 3). The agreement was in the same range as found for the various "Top-Down" and "Bottom-Up" methods, if all are considered separately. Differences in "Top-Down" estimates also reflect the different source areas sampled for available energy and for turbulent fluxes.

Canopy conductances were derived from sap flow data (Granier et al., 1995; Köstner et al., 1995; both this issue) and micrometeorological data (Bernhofer et al., 1995, this issue) as illustrated in Fig. 5. A strong daily increase occurs in canopy conductance with increase in radiation

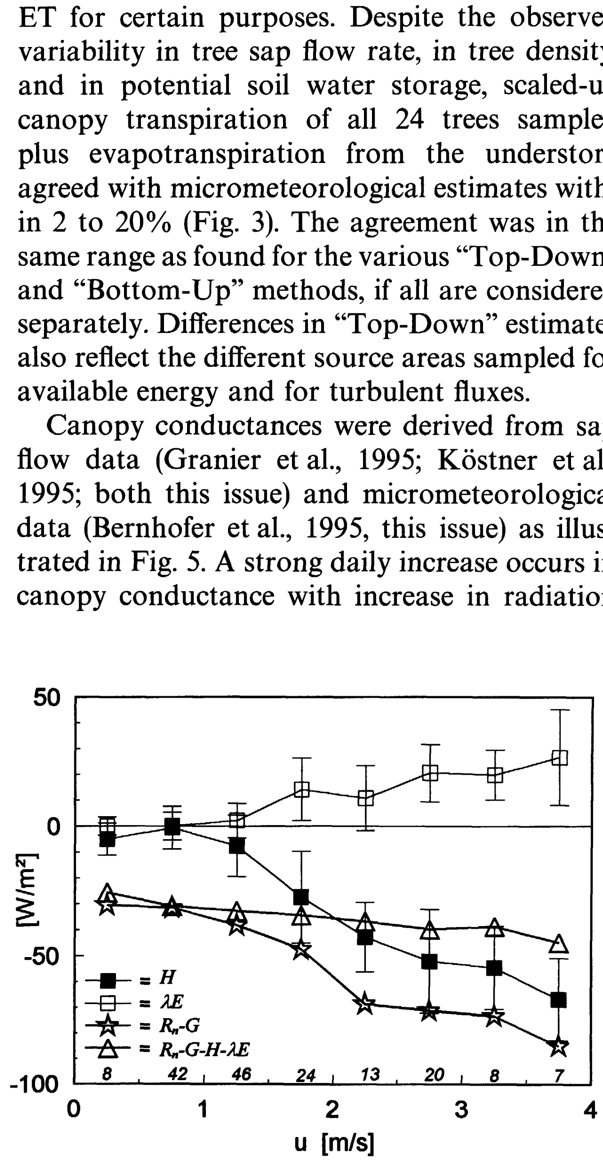

Fig. 4. Average night-time (available energy $R_n - G < 0$) fluxes and standard deviations of turbulent fluxes (sensible flux H, and latent flux λE), available energy ($R_n - G$) and closure gap ($R_n - G - H - \lambda E$) grouped according to wind speed u in classes of 0.5 m/s over the Hartheim Scots pine plantation. Turbulent fluxes are averages of three sonic EC systems (17 m, 22 m and 28 m above ground mounted at the large tower of the University of Freiburg) with error bars illustrating differences of EC levels; bottom row gives number of samples per wind class (from Vogt, 1995)

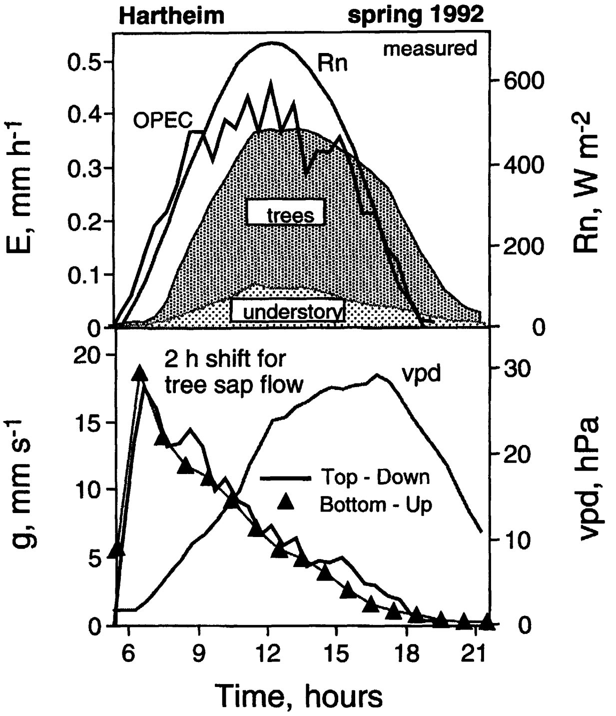

Fig. 5. Comparison of "Top-Down" eddy-covariance measurement of stand evapotranspiration with "Bottom-Up" estimate based on tree sap flow plus understory flux as described by Bernhofer et al. (1995), Vogt et al. (1995), Granier et al. (1995), Köstner et al. (1995), and Wedler et al. (1995b); all this issue. Upper panel: OPEC is the one-propeller eddy covariance method of Blanford and Gay (1992), and Gay et al. (1995a, this issue). Water flux from trees and understory is additively shown. E is evapo-transpiration, R_n is net radiation flux. Lower panel: Solid line is conductance from OPEC, solid triangles indicate conductance of trees plus understory with time shift to account for lag in flow (see Granier et al., 1995, this issue)

and a decrease with increasing vapor pressure deficit, findings that are in general agreement with Jarvis (1976) and others. The "Omega factor" as used by McNaughton and Jarvis (1983) ranged from 0 to 0.15 during the daylight period, indicating a strong coupling between canopy and atmosphere. Stand transpiration may, therefore, be effectively described as a function of radiation and vapor pressure deficit for short periods and until changes in soil moisture modify stomatal behavior.

2.2 Carbon Dioxide Fluxes

CO_2 gas exchange was measured for *Pinus silvestris* needles on trees adjacent to the towers over diurnal courses as described in Bernhofer et al. (1995, this issue) and Joss (1995) and for understory species as summarized by Wedler (1995a; this issue). A detailed analysis of carbon fixation fluxes of pine branches and the tree overstory will be reported elsewhere (Tenhunen et al., 1995). Nevertheless, the preliminary yet carefully checked simulation results which up-scale the leaf-level measurements to the canopy during HartX are summarized to complete the picture with respect to stand carbon balance and water use efficiency.

Net CO_2 uptake varied between 3 and 6 mmol/m^{2}s on a projected area basis at midday for needles of branches in the sun crown on May 17 and 18, 1992 and remained between 1 and 3 mmol/m^{2}s for shade crown branches. Analysis with a model that permitted response comparison under similar conditions suggested that both sun and shade needles exhibited the same photosynthetic capacity of about 7 mmol/m^{2}s at light saturation. Thus, the differences in uptake rates and also the differences in leaf conductance observed under natural environmental conditions are mainly due to canopy effects on microclimate. Greater water use efficiency occurs in the shade crown.

Maximum daily carbon uptake estimated with a multi-layer canopy model was about 425 mmol/m^2 day. Modelled daily transpiration decreased in a similar manner to tree transpiration measured with sap flow methods during the last five days of HartX. This occurred in response to decreasing vapor pressure deficit (Fig. 2) and despite increasing conductance under these conditions. Simulated canopy carbon dioxide uptake decreases only slightly during this period (from 425 to 375 mmol/m^2 day), since the temperature response curve is relatively flat and because stomatal opening leads to increases in needle internal CO_2 and net photosynthesis. Thus, water use efficiency increased during the latter days of HartX.

3. From Anchor Point to Grid Point

Due to its favorable fetch and homogeneity, the long-term record of ecological and meteorological monitoring, and on-going efforts to evaluate energy balance in the Upper-Rhine Valley within the regional climate project REKLIP (Parlow, 1995, this issue) the Hartheim plantation site is well-suited to serve as an anchor point within regional- and continental-scale climate studies. Such anchor points can serve as reference areas for climate model calibrations and testing, for the development of flux aggregation schemes for representative landscapes, and for remote-sensing ground-truth measurements at various spatial scales. Only limited efforts could be made to date with regard to extending the findings during HartX to a greater area.

Wüthrich (1995, this issue) demonstrates that the major variation in surface characteristics and exchange in the upper Rhine Valley REKLIP area (Parlow, 1995, this issue) occurs between agricultural fields, forests and urban areas. Minor variation in surface temperatures were found within the Scots pine plantation, apparently due to clearings, changes in species composition (*Pinus nigra* occurs at a number of locations), and tree height. Nevertheless, these small scale variations could be indicative of exchange process variation that is in fact related to the observed gap in energy balance closure as found in the EC measurements (Vogt, 1995). Additionally, Ernst and Wüthrich (1995, this issue) showed that the plantation, with greater roughness than the surrounding agricultural fields, was the center of a weak local circulation due to differential heating/cooling on at least one clear night during HartX. Results of Wicke and Bernhofer (1995, this issue) suggest that local circulation can be caused by the different energy partitioning at forest and agricultural locations (forest ET was only 50 to 80% of grass ET at the comparison site monitored). In turn, local advection will affect energy partitioning at neighbouring sites. Remote sensing could potentially be used to evaluate the size and intensity of differentially heated plots associated with this phenomenon and modelling might be undertaken to close the gap between micrometeorological and hydrological methods for assessment of water balance (see Fig. 1).

4. From Measurement Campaign to Long-term Ecological Monitoring

4.1 Stand History

After closure of the tree canopy occurred, there was little or no understory vegetation at the Hartheim plantation. Stands were thinned in 1982 to reduce tree density from 8730 trees/ha to 6400 trees/ha and in 1991/1992 to further reduce density to about 4000 trees/ha (Jaeger and Kessler, 1995, this issue). In association with thinning and tree aging, a substantial understory developed which at the time of HartX resulted in forest floor ET of about 20% of total evapotranspiration (Wedler et al., 1995b, this issue). Despite long-term study at this site, important discrepancies occur and uncertainties are found among the estimates of essential biometric values (e.g., stems/ha, LAI, stem area index, etc.). Thus, it is essential that continuous consistent monitoring be carried out in the future not only with respect to functional but also ecosystem structural variables. This and perhaps introduction and careful monitoring of various treatments that influence soil characteristics must be taken into account when assessing long-term interrelationships in the soil-vegetation-atmosphere system and modelling the biosphere for climatic change purposes (especially at the mesoscale).

4.2 Long-term Measurements

The very good agreement obtained during HartX between sophisticated EC measurements of sensible heat flux and a simplified one dimensional propeller system (OPEC, Blanford and Gay, 1992; Gay et al., 1995a, this issue) as well as the proven durability of the latter system support the reliability of continuous long-term OPEC energy balance descriptions for a six-month period during summer and fall 1992 (Gay et al., 1995b, this issue). These results indicate a low Bowen ratio in June and increasing Bowen ratio values in July and August in correspondence with water stress and stomatal closure that limits latent heat flux at the Hartheim site in summer (see also Kessler et al., 1988; Jaeger and Kessler, 1995, this issue). The hydrological balance as determined from measurements of soil moisture and precipitation was used for comparison over the entire period and agreed within 5% with those estimated from OPEC. We recommend the OPEC system as a cost effective method for long-term water flux measurements and for redundant measurements when more sophisticated EC instrumentation is available.

For long-term monitoring of net ecosystem carbon balance by the EC method special emphasis should be placed on examining night-time exchange processes. This is apparent from Fig. 4 (from Vogt, 1995) where water vapor is utilized as a "dummy scalar" for carbon dioxide. It depicts available energy, turbulent fluxes and closure gap grouped according to wind speed during the night-time period. As wind increases, mechanical mixing triggers the onset of turbulent transport at a wind speed of about 1.5 m/s. Both sensible flux to the ground and latent flux from the ground increase with higher wind speeds. However, reduced cooling of the canopy surface (resulting in more negative available energy) and the difference in sign of the fluxes result in an increase of the observed closure gap from 30 to 50 W/m^2 with increasing wind speed. With respect to water flux, a correction scheme can be developed similar to the one proposed by Gay et al. (1995a, this issue) such that reliable daily water flux totals are obtained.

With respect to the exchange of carbon dioxide, insufficiencies in flux description by EC can strongly bias estimates of net ecosystem carbon gain, especially if the inaccuracies are greater during night (periods of respiration) than during the day (periods of CO_2 fixation). Simultaneous measurements of turbulent heat fluxes and the utilization of the energy balance are essential components of any carbon balance study, since they provide the potential for an independent evaluation of bias in the EC estimate of measured carbon fixation. Additionally, HartX has demonstrated to us the value of supplementary cuvette measurements to elborate the functional dependencies controlling flux rates in various ecosystem compartments (soil, stems, branches and leaves). Future studies must utilize a suite of techniques applied simultaneously in order to reduce uncertainties and better understand system process linkages.

5. Discussion and Conclusion

At Hartheim, the addition of direct estimates of water vapor flux from the forest floor and the tree canopy led to total flux approximations that were similar to total water vapor flux measured with an eddy covariance energy balance system (OPEC, see Blanford and Gay, 1992). Tree transpiration plus understory evapotranspiration agreed with daily micrometeorological estimates to within 2 to 19% (average deviation for 8 days was 8%). Considering a time lag of 1.5 to 2 hours between the onset of tree canopy transpiration and measurements of sap flux on the lower trunk (Granier et al., 1995, this issue), the time course of total conductance including trees and understory agreed with stand surface conductance (Fig. 5).

Under conditions with high radiation input, high vapor pressure deficit, and sufficient soil moisture (Gay et al., 1995a; Jaeger and Kessler, 1995; Sturm et al., 1995; Vogt et al., 1995; all this issue), evapotranspiration rate was similar to that found for the long-term mean for May and midday depression was not detected (compare Kessler et al., 1979; Schott, 1980). However, after an early morning maximum of canopy conductance with about 18 mm/s was attained, a distinct reduction was observed in correlation with increases in vapor pressure deficit up to 30 hPa (see Fig. 5; Bernhofer et al., 1995; and Granier et al., 1995; both this issue). The relatively low evapotranspiration – despite high atmospheric demand – results due to water transport limitations in the roots, trunks and brances of trees, site specific long-term development of LAI, and site specific stomatal regulation of water loss.

As a result of the agreement between "Top-Down" and "Bottom-Up" observations, several important conclusions may be reached. Under favorable measurement conditions and with careful application, both approaches will provide reasonable estimates of vegetation-/atmospheric coupling. Interdisciplinary studies in which these approaches are simultaneously used will allow us to establish efficient new procedures for data collecting and for constructing soil-vegetation-atmosphere transfer models (SVATs). New strategies must be developed employing these alternative approaches to achieve an understanding of i) area average fluxes, ii) relative contribution of differing biological sources to total fluxes, iii) relative potentials of biological objects to control fluxes, iv) variation in flux rates within individual plants, vegetation patches, and landscapes, and v) the role of turbulent exchange for the evaluation of the net ecosystem carbon balance, considering the observed failure of the EC method to close the energy balance, especially at night.

Success of the experiment in Hartheim which was conducted under extremely favorable conditions (homogeneous stand structure, long fetch distance, and a series of days with similar weather) gives us new confidence to undertake similar experiments with greater inherent difficulties and risk. Despite this general agreement in flux estimates, we have to recognize the need to conduct such experiments over the long-term in order to better explain measured differences. Only through long-term observations will it be possible to identify systematic differences in data obtained by "Top-Down" and "Bottom-Up" methods that may provide further insight with respect to remaining differences in evapotranspiration and – to an even higher degree – carbon exchange estimates.

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