5. Summary and Conclusions

Flux measurements were conducted by means of the micrometeorological eddy correlation (EC) technique in the 1999 growing season over a temperate humid grassland located in the Environmental Research Center (ERC), University of Tsukuba, about 50 km to northeast of Tokyo. This kind of grassland is commonly distributed in the Kanto Plain of Japan. The ERC grassland was composed of 54 species (46 C3 species and 8 C4 species). C3 species, *Solidago altissima* and *Festuca arundinacea,* dominated the cold season including late spring, early summer, and late autumn, while C4 species, *Imperata cylindrical* and *Miscanthus sinensis* dominated the warm period from mid-summer through early autumn.

Eddy correlation (EC) technique was employed to determine latent heat (*LE*) and sensible heat (*H*) flux densities over the grassland. The EC measurement system was evaluated by closing the energy balance and by comparing the results with measurements using a micro-lysimeter. The sum of *H* and *LE* was in good agreement with the available energy (Q_n, net radiation flux density minus soil heat flux density) throughout the growing season except for the senescent period. Evapotranspiration (ET) estimated by EC was consistent with ET measured directly with the lysimeter. Hence, the EC measurement system in the present study is reliable in estimating heat and mass fluxes. Nevertheless, uncertainties appeared when assessing the closure regime on a basis of different growth stages of the canopy. The closure was not achieved under poor fetch. Heterogeneity caused by height growth for flowering and patch-like senescence made the canopy surface aerodynamically much rougher, which remarkably affected the closure.

Daily variations in *LE* followed approximately those in the available energy and peaks about 1 to 2 h later than Q_n does. Daily trends in *H* were different from those for

Q_n and *LE* in that *H* reached its peak values in the mid-morning and changed sign about 1 to 2 h earlier than *LE*. Sensible heat advection was significant on clear days during most of the measurement period. Bowen ratio (β) was generally larger in the mid-morning and declined thereafter, becoming negative in the late afternoon. Evaporative fraction (*EF*), the proportion of Q_n that is partitioned into *LE*, displayed an inverse daily pattern to β. Dark evapotranspiration was very small and might be primarily driven by the sensible heat flux density.

During the course of the growing season, energy budget and net canopy CO_2 flux density is determined by changing microenvironmental, eco-physiological and phenological conditions of the grassland. A clear seasonal pattern of the partitioning of Q_n into *LE* and *H* was observed for the ERC grassland. *LE* dominated the daily energy budget during the rapid growth period and the closed canopy period. Bowen ratios in midday (09:00 to 14:00 JST) were generally less than 0.60 and approached the minimum in late July to early August when the canopy closed and soil moisture was plentiful. *H* dominated the daily energy budget during the flowering period and the senescence period. Midday values of β were generally greater than unity on most clear days. On most measurement days *EF* was generally greater than 50% with peak values of about 90% just after the *Baiu* rain period ended and the canopy closed. *EF* decreased as the grasses aged.

The omega factor (Ω) was employed to assess to what extent evapotranspiration (ET) was determined by the available energy and to what extent ET was determined by such factors as the atmospheric evaporative demand, the canopy surface conductance and the sensible heat advection. Values of Ω were generally largest in the mid-morning and decreased from the morning through the afternoon. This pattern implies that Q_n was the principal determinant in evaporating water from the canopy surface in the morning hours while the canopy stomatal conductance and/or the atmospheric evaporative demand (or the sensible heat advection) became dominant in the afternoon hours.

Midday values of Ω were generally larger than 0.7 throughout the growing season.

This result is comparable to the values reported by McNaughton and Jarvis (1983) and Jarvis and McNaughton (1986) for grasslands and crops. However, there was a tendency that values of Ω decreased with progression of the growing season. This was because the grassland canopy surface becomes rougher due to flowering and patch-like aging of *Solidago altissima* and *Miscanthus sinensis*. Sensible heat advection, if exists, in part at least, interprets this pattern.

LAI was an important governing factor in the partitioning of the available energy before the canopy closed. However, when the canopy was closed or LAI maintained relatively stable levels, the partitioning of the available energy was controlled by other factors, mainly energy gain from the solar radiation, rather than LAI. Apparently, as grasses senesced, the partitioning was guided to some extent by evaporative capacity of effective LAI.

Daytime net canopy CO_2 flux density (F_c) and incident photosynthetic photon flux density (PPFD) fluctuated approximately, implying that F_c was PPFD-dependent. This pattern was maintained throughout the growing period. The peak F_c values ranged from 7.3 (DOY 304) to 56.7 (DOY 231) μ mol m^{-2} s^{-1}. Nighttime F_c varied between −1.3 during the period prior to the canopy closure and −21.6 μ mol m^{-2} s^{-1} during the closed canopy period. Usually peak net carbon losses were observed just after sunset when air temperatures were relatively high. The maximal diurnal integrated F_c (NEE) was 1.06 mol m^{-2} d^{-1} (DOY 234).

A clear seasonal pattern for the F_c was observed. The daily-integrated net canopy CO_2 flux density was largest (0.75 ± 0.36 mol m^{-2} d^{-1}, mean ± SD) during the rapid growth period when canopy microenvironmental and eco-physiological conditions were optimal. The greatest net carbon gain occurred early in the closed canopy period, but NEE was relatively lower (0.60 ± 0.58 mol m^{-2} d^{-1}) as compared to the rapid growing period, suggesting that respiration from the soil and plants accounted for a considerable loss from the canopy. With progression of the growth stage, NEE was reduced due to decreasing photosynthesis. We attribute a general larger reduction in NEE during the senescent period both to low levels of PPFD and to reduction of capability of grasses to assimilate CO_2 as a result of aging. Frost events during the late senescent period caused abrupt decrease in NEE. NEE is sensitive to cloudiness. The ERC grassland became a source, releasing CO_2 to the atmosphere, on most overcast days. As a whole, the ERC grassland, without soil moisture deficit, is highly productive and is a sink for atmospheric CO_2 over most of the growing season.

Because both ET and F_c are usually tightly coupled with incident energy and follow a similar temporal pattern, mechanisms that determine their dynamics is the same in terms of canopy surface conductance (g_c) and water use efficiency (WUE). Both g_c and WUE peaked in the morning followed by an almost linear decrease. Midday (09:00 to 14:00 JST) g_c values varied between 2.4 mm s^{-1} during the senescent period to 11.2 mm s^{-1} during the rapid growth period. Midday WUE values ranged from 12.0 to 18.7 mg CO_2 g^{-1} H_2O. Generally, g_c and WUE followed similar daytime trends: higher in the morning and lower in the afternoon. Because of this similarity, the factors that affect g_c may also contribute to WUE. Therefore, the incident energy (the available energy, Q_n or PPFD) was dominant in the morning hours while higher VPD in conjunction with occurrence of SHA, which might result in partial closure of stomata, might be responsible for appreciable lower g_c and WUE values in the late afternoon. This is consistent with the results of omega factor analysis. Both g_c and WUE were sensitive to lower PPFD and had a tendency to decrease with increasing VPD.

Daytime F_c increased with increasing incident PPFD in a rectangular hyperbolic manner with a coefficient of determination higher than 0.7 over the entire growing period. For each of the growth stages, however, this relationships display different features reflecting different in situ microenvironmental and ecophysiological conditions, especially in air temperature and VPD, under which the measurements were made. Modeled mean dark respiration ranged from –2.45 to –11.15 μmol m^{-2} s^{-1} and was comparable in magnitude with the nighttime mean F_c measured directly with the EC technique.

The initial slope of the F_c-incident PPFD relationship at low PPFD (< 500 μ mol m^{-2} s^{-1}), F_c at PPFD = 2000 μ mol m^{-2} s^{-1}, the canopy light compensation point, and the mean dark respiration all show distinct seasonal patterns and were affected greatly by air temperature (T_a) and vapor pressure deficit (VPD). The initial slope (light-use efficiency) varied from 0.015 mol CO_2 mol^{-1} during the senescent period to 0.043 mol CO_2 mol^{-1} during the closed canopy period with an average of 0.033 mol CO_2 mol^{-1} photon. The canopy was not efficient in light-use as it aged. The canopy light compensation point ranged from 140 to 250 μ mol m^{-2} s^{-1} with an average of 210 μ mol m^{-2} s^{-1}. The canopy light compensation point decreased with progression of the growth stage.

Responses of nighttime F_c to air temperature (T_a), when wind speed measured at 1.6 m was larger than 0.5 m s^{-1}, were fitted to an exponential function. The temperature coefficient, Q_{10}, was about 4.9 when averaged over the entire growth period. Q_{10} varied in response to the growth stages of the canopy. In addition, nighttime F_c was well coupled with sensible heat flux density reflecting the effect of turbulence on nighttime flux.

Comparisons were made of the canopy-level and leaf-level flux measurements. Daily trends in F_c, g_c and WUE of the canopy were similar to those on individual leaves of dominant species, suggesting that the canopy architecture in terms of species composition and its seasonal dominance transition may be an important factor affecting dynamics of the flux densities. Leaf area based F_c was lower in magnitude than net photosynthesis rate measure on individual leaves. WUE and g_c, estimated from the Penman-Monteith model, of the canopy during the canopy closure period were on the same order of their counterparts of the leaves. The hyperbolic modeling results demonstrate that the initial slope for the canopy was on the same order of magnitude as those for the individual leaves of dominant species, indicating the canopy was very efficient in light-use. Generally, the canopy displayed light-saturation under much higher levels of PPFD than individual leaves.