1 General Introduction

1.1 The global warming and terrestrial ecosystems

The Earth is becoming warmer and warmer as a result of the so-called greenhouse effect caused by anthropogenic unreasonable uses of natural resources such as increasing combustion of fossil fuels, deforestation, ozone depletion, and inappropriate agricultural practices (Keeling et al., 1995, 1996a, b). Atmospheric CO_2 concentration has increased from 280 ppm at the beginning of the Industry Revolution of 18's century to the current level exceeding 360 ppm (Bazzaz et al., 1996). It is still increasing at a rate of about 1.5 ppm per year and will amount to *c*. 600 ppm (around 2 times pre-industrial levels) if effective measures of CO_2 or air temperature rise-stopping are executed, being accompanied by global warming of about 3°C by the mid 21 century (IPPC, 1996; Hasselmann, 1997).

The greenhouse effect and resultant climate change exert increasingly profound influences upon various terrestrial ecosystems (e.g. Gerard et al., 1999; Houghton, 1996; Houghton et al., 1998; Lashof et al., 1997; Saleska et al., 1999; Schulze et al., 1996, 1999; Sellers et al., 1996a; Wang and Polglase, 1995). Meanwhile, the terrestrial ecosystems can play most critical roles in controlling regional and global climate through their effective heat and mass exchanges within the soil-plant-atmosphere continuum (SPAC) or a so-called biological feedback mechanism, especially adjusting atmospheric CO_2 concentrations (e.g. Bonan et al., 1992; Dixon et al., 1994; Francey et al., 1995; Goulden et al., 1996a; Korner and Arnone III, 1992; Phillips et al., 1998; Schlesinger et al., 1990; Tans and Balkwins, 1995; Wofsy et al., 1993). However, we still lack information on the magnitude and dynamics of these exchanges, the amount of carbon release and storage in particular, and the mechanisms that control these processes over large time and space scales for most of the terrestrial ecosystems (Jarvis and Dewar, 1993; Sellers et al., 1997a).

Therefore, a better understanding of the interaction between the atmosphere and the terrestrial ecosystem is fairly important in predicting future climate change and dynamics of terrestrial ecosystems.

1.2 Techniques to deal with the relationship between the atmosphere and terrestrial ecosystems

To deal with the interactions between the atmosphere and vegetated land surfaces, their roles in the global carbon cycling, and the effects of the global warming upon them, a number of techniques have been developed over past 80 years including simulation and modeling techniques, micrometeorological techniques, and enclosures, among others. These techniques may be scale-oriented but are closely related to one another.

1.2.1 Simulation and modeling

A large number of computer models and computer-based simulations have been developed over the past two decades to reveal the water and carbon dynamics of different terrestrial ecosystems and their relationships to the global climate change potentially caused by the greenhouse effect (e.g. Amthor et al., 1994; Baldocchi, 1992; Coughenour and Chen, 1997; Friend and Cox, 1995; Harley and Baldocchi, 1995a, b; Huntingford et al., 1995; Katul and Albertson, 1999; Meyers and Paw U, 1986; Oikawa, 1995, 1998; Susuki et al., 1993). The SiB (the Simple Biosphere model) and its improved version SiB2 are the most famous models that have been widely used in implementation of GCMs (General Circulation Models) (Sellers and Dorman, 1987; Sellers et al., 1986, 1996b, c, 1997b).

Models and simulations are effective methods to predict climate change and its impact to the terrestrial ecosystems on relatively larger temporal and spatial scales. They may, however, have limitations or shortcomings when scaling-down and scaling-up because the size and spacing of their grid cells is often larger than real landscapes on the Earth, which are often characterized by discontinuous distribution and significantly spatial heterogeneity (Jarvis, 1995b). Therefore, relative larger scale surface-based experiments, at least at canopy or community scale, are requisite to validate and improve the reliability of models and simulations (scaling-up). Over the past two decades, several international programs have been executed to assess the interactions of the atmosphere and terrestrial ecosystems, for example, HIFE (the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment, Hall and Sellers, 1995; Sellers et al., 1992; Sellers and Hall, 1992), HAPEX (the Hydrological-Atmospheric Pilot EXperiment, Goutorbe et al., 1994, 1997), NOPEX (the Northern Hemisphere Climate-Processes Land-Surface Experiment, Cienciala and Lindroth, 1999; Cienciala et al., 1998; Halldin et al., 1998; Lundin and Halldin, 1994a, b), and BOREAS (the Boreal Ecosystem Atmosphere Study, Sellers et al., 1995, 1997) (summarized in Appendix 1). Obviously, these experiments contribute much to drawing a global flux map and a deep understanding of the essence of the interaction between the terrestrial ecosystems and the global change, especially the global warming induced by the greenhouse effect. However, more information on the energy and mass exchanges in various terrestrial ecosystems is still required in studies of modeling and simulations.

1.2.2 Enclosure techniques

OTC (Open Top Chamber) and FACE (Free Air CO_2 Enrichment) techniques, the artificial greenhouse effect chambers, phytotrons, and portable measuring systems like IRGA (Infra-Red Gas Analyzer) are very useful in monitoring short-term changes of plants under the simulated regime of the global warming (e.g. Curtis, 1996; Ellsworth et al., 1995; Grant et al., 1995a, b, 1999; Hendrey et al., 1999; Jordan et al., 1999; Kimball et al., 1993, 1994, 1995; Leadley and Drake, 1993; Lüscher et al., 1998; Norris et al., 1996a, b; Norton et al., 1999). Reliability and representativeness of the enclosure techniques are often questioned because enclosure often gives rise to a disturbance to objects studied and an edging effect occurs. They may also meet restrictions when scaling-up because these measurements are usually conducted with leaves, individual plants, or a section of community. The micrometeorological techniques provide possibility to overcome these restrictions. Actually, our understanding of the dynamics of fluxes over the ecosystems in large scales over the past decades relies on the micrometeorological techniques (Baldocchi, 2000, Baldocchi and Meyer, 1998).

1.2.3 Micrometeorological techniques

Among a variety of methods to estimate the exchange of mass and energy between the atmosphere and terrestrial ecosystems, micrometeorological techniques are most common and probably most appropriate since they do not perturb the surface microenvironment conditions, have advantages in their directness and accuracy, and intermediate in spatial and temporal scale as compared to modeling and closure techniques (Baldocchi, 1997, Baldocchi and Meyer, 1988a, b; 1998; Baldocchi et al., 1996). At present, therefore, the micrometeorological techniques, especially the eddy correlation (EC) technique, are strongly recommended by the scientific community when conducting spatially and temporally integrated flux measurements over the terrestrial ecosystems. With great improvement of instruments for measuring wind speed and scalars, especially trace gases, the micrometeorological techniques now have been used routinely to reveal ground-based relationships between terrestrial ecosystems and the atmosphere.

During recent decades, the micrometeorological techniques have been extensively employed to quantify the CO_2 and water vapor fluxes over many types of surfaces, for example, forests (Black et al., 1996; Fan et al., 1990; Gower et al., 1997; Grace, 1995a, b, 1996; Greco and Baldocchi, 1996; Hollinger et al., 1999; Malhi et al., 1999; McCaughey et al., 1997; Pattey et al., 1997; Price and Black, 1990, 1991), agricultural crops (e.g. Baldocchi and Rao, 1995; McGinn and King, 1990; Ontaki and Oikawa, 1991; Steduto et al., 1998a, b,c), peatland (Verma et al., 1992b), tundra (Oechel et al., 1993, 1995; Vourlitis and Oechel. 1997, 1999; Whiting et al., 1992), and grasslands (Colello et al., 1998; Ham and Knapp, 1998; Ham et al., 1995; Kim et al., 1992; Norman et al., 1992; Polley at al., 1992; Verma et al., 1989). These field-based micrometeorological investigations provide good data for testing and improving models and simulations and facilitate extrapolation of site measurements to regional or even global scales.

1.3 Grassland in context of the global terrestrial ecosystems

Recent studies of the global annual carbon budget indicate that there exists a 'missing sink' of *ca.* 0.4 to 4.3 Gt C yr^{-1} that is not accounted for (Gifford, 1994; Keeling et al., 1996a, b; Tans et al., 1990). Hence, the "missing" sink must exist somewhere on the Earth (Fan et al., 1998; Ker et al., 1992). Some of the global terrestrial ecosystems are possible candidates for the missing sink. Estimates of annual net ecosystem CO_2 exchange (NEE) via modeling and experiments suggest that most of tropical, temperate and boreal forests of the northern hemisphere can sequester some of the anthropogenic carbon emissions not accumulating in the atmosphere (e.g. Ciais, 1999; Ciais et al., 1995; Denning et al., 1995, 1999; Dixon et al., 1994; Gifford, 1994; Jarvis et al., 1997; Malhi et al., 1999; Schimel, 1995; Schimel et al., 1991; Schindler, 1999; Sundquist, 1993). Arctic tundra ecosystems are considered to be sinks or sources for atmospheric CO_2 in response to soil surface moisture conditions (Oechel et al., 1993).

Grassland ecosystems account for approximately one third of the Earth's natural vegetation and covers both eastern and western hemispheres (Adams et al., 1990). It does not distribute continuously in the many parts of the Earth. Its patch-like distribution is commonly found in the lower latitude where landscape is heterogeneous in composition. Most grasslands are neighboring forests, croplands and residential areas. Like other terrestrial ecosystems, the grassland ecosystems have the potential to affect the global carbon budget through sequestration of CO_2 from the atmosphere (photosynthesis and storage of C in the soils) and release of CO_2 to the atmosphere (respiration) (Parton et al., 1995). Savannahs probably contribute to closing the regional and possibly global carbon budget depending on seasonality (wet or dry season) (Fisher et al., 1994; Verhoef et al., 1996). Tropical grasslands are sinks for atmospheric CO_2 due to their appreciable amount of assimilation and storage of carbon in the soil (Scurlock and Hall, 1998). One of the most widely studied temperate grassland ecosystems is the Konza Prairie in northeastern Kansas, USA (e.g. Dugas et al., 1997, 1999; Ham and Knapp, 1998; Sellers and Hall, 1992). Up till now, however, very little information on whether the humid temperate grasslands are sinks or sources of CO_2 is available in the literature. Hence, to acquire a clear understanding of both the effects of global change on grasslands and the roles played by grasslands in modulating of global change (mainly alleviation of global warming), it is potentially significant to investigate dynamics of net ecosystem CO_2 flux density between the humid temperate grassland ecosystem and the atmosphere for a reasonable temporal scale.

It is well documented that C4 plant functional types (PFT) have greater efficiency of water use and nitrogen use, require higher light intensity for photosynthetic saturation, and have higher temperature optima for photosynthesis than C3 PFTs (Berry and Björkman, 1980; Jones, 1992; Larcher, 1995; Smith et al., 1997; also see Appendix 2). Both elevated temperature and CO_2 concentration affect morphological, biochemical, phenological, and eco-physiological features of C3 and C4 PFTs. Under enriched CO_2 conditions (higher than the current ambient level), plants often develop larger leaves, their photosynthesis is enhanced and their transpiration is reduced, their stomatal behavior is altered (generally, stomatal conductance is reduced), and their shoot-to-root ratio and allocation pattern of nitrogen and carbon is also affected (e.g. Ceulemans et al., 1995; Chen et al., 1996; Coleman and Bazzaz, 1992; Cowling and Sage, 1998; Eamus, 1991, 1996; Ehleringer, et al., 1997; Farrar, 1991; Field et al., 1995; Hendrey et al., 1993; Hunt et al., 1991, 1996; Idso and Idso, 1994; Jackson et al., 1994; Kimball et al., 1994, 1995; Rawson, 1995; Read and Morgan, 1996; Schlesinger, 1993; Wolfe et al., 1998). The global warming commonly prolongs the growing season of plants (Ham et al., 1995).

Generally, grasslands in the temperate zone are characterized by co-occurring C3 and C4 plant species. Seasonal dynamics of species composition in the grassland community demonstrates that C3 plants dominate the season with lower air temperature and C4 plants dominate the period with higher air temperature (Kemp and Williams III, 1980; Monson and Williams, 1982; Monson et al., 1983; Newton et al., 1994; Paruelo and Lauenroth, 1996; Rundel, 1980; Teeri and Stowe, 1976; Vogel et al., 1986; Williams III, 1974). Therefore, the global warming, characterized by elevated greenhouse gases and resultant air temperature increase, may affect the spatial and temporal patterns of interplays of the grassland and the atmosphere through its effect upon phenological and eco-physiological performance of C3 and C4 species that dominate grasslands. To clarify the canopy-scale relationships between the grassland and the atmosphere could help reveal those patterns and provide the possibility to relate the canopy-scale energy and mass exchanges to important environmental, eco-physiological and phenological variables. Furthermore, to improve our knowledge on the mechanisms underlying surface exchanges, there is a necessity for pay much attention to the interaction between the atmosphere and the ecosystems characterized by mixture of C3 and C4 plant species, especially the temporal and special dynamics under the global change.

1.4 Purposes of the present study

With the increasing interest in the global warming and especially in the different responses of C3 and C4 plant species to such environmental changes as elevated CO_2 concentration and air temperature, and also with requirements for offering credible and ground-based data to improve the accuracy of the models and simulations and to find "missing" sink of the atmospheric CO_2, it is becoming considerably important to conduct research on the relationship between the eco-physiological features of C3 and C4 co-occurring grassland and the CO_2, H_2O, and energy fluxes over the grassland.

A humid grassland, which developed from red-pine forest clearcut in the Kanto plain of Japan, was selected as an experimental field for flux measurements. The experimental site is located at the Environmental Research Center (ERC), University of Tsukuba. The ERC grassland has a characteristic mixture of C3 and C4 perennials. Dominance of C3 or C4 species changes seasonally in terms of leaf area index (LAI) and biomass (Tanaka and Oikawa, 1999).

An experimental study was conducted by Saigusa et al. (1998) to understand seasonal variations in CO_2 and H_2O exchanges over this field using the aerodynamic gradient method. Further studies are strongly needed because the magnitude and dynamics of these exchanges, the mechanisms that controls these processes over large time and space scales, and their relationships to the seasonal development of the plant canopy have not yet been well investigated. For this purpose, we used the eddy correlation technique and the eco-physiological techniques to conduct further study of the interactions of the atmosphere and the ERC grassland and their mechanisms governing the interactions.

The primary objectives of this paper are to: 1) evaluate the performance of the EC measurement system and their affecting factors, 2) examine the diurnal and seasonal patterns of energy budget and CO_2 flux, 3) clarify environmental and ecophysiological variables factors determining these patterns, 4) reveal some differences of CO_2 exchange (photosynthesis) at leaf and canopy scales of the grassland. In the present study, however, we do not attempt to partition fluxes into the contributions from C3 and C4 plant species.

1.5 Composition of this paper

Section 1 introduces the global warming and its association with terrestrial ecosystems, some techniques dealing with the interaction between the atmosphere and the terrestrial ecosystems, some features of grassland ecosystems and the roles played by the grasslands in the global energy and mass balance, and the purpose of the present study on the energy budget and CO_2 flux over a C3 and C4 co-existing grassland using the eddy correlation technique.

Section 2 presents materials and methods including site descriptions, experimental design, instruments used in flux measurements and their field deployment, the measurement of canopy height and leaf area index, data processing methods, and data screening procedure.

Section 3 reports the microenvironmental conditions during the measurement period, dynamics of the grassland canopy in terms of canopy height and leaf area index, performance of the eddy correlation measurement system, diurnal and seasonal patterns of energy budget components, and diurnal and seasonal patterns of net canopy CO_2 flux and water use efficiency.

Section 4 discusses whether or not the eddy correlation measurement system in this study is reliable in determining the fluxes and what factors affect performances of the system, how the available energy over the grassland is partitioned on diurnal and seasonal scales and what forces are responsible for the partitioning, and how the net canopy CO_2 flux density above the grassland canopy varies on daily and seasonal time scales and responds to environmental and ecological factors.

Section 5 summarizes the results obtained from the experiment.