1. TITLE

Measuring and Modeling Carbon, Water Vapor and Energy Exchange over Grassland and Tree/Grass Ecosystems

PROJECT SUMMARY

Western savanna ecosystems are among the most complex ecosystems to be studied by biometeorologists. They are horizontally and vertically heterogeneous, they experience summer water deficits, and they rely on a multiple plant functional approaches to acquire carbon and manage water loss. At present, savanna ecosystems are poorly represented in the AmeriFlux network. Yet, savannas constitute a major ecosystem and are analogs for studying how the carbon metabolism of ecosystems will respond to environmental perturbations.

We propose to study the roles of climate and ecosystem structure and functionality on carbon and water fluxes of an oak/grass savanna and a grassland. This study will provide information on how broadleaved forests, in AmeriFlux, respond to changes in soil moisture. It will broaden the range of climate variables, canopy structure and functionality that is currently under study by the network.

The eddy covariance method will be used to measure flux densities of CO₂ and water vapor. Portable eddy flux systems will be deployed in the surface layer and understory of the savanna to augment the tower-based flux measurements. Physiological capacity, sap flow and soil-root respiration will be measured to evaluate fluxes associated with constituent compartments. Our objectives are to assess: 1) the relative contributions of vegetation and the soil on CO₂ and water vapor exchange; 2) spatial variability of understory fluxes; 3) the impact of sloping terrain on the interpretation of flux covariances. A biophysical gas exchange model (CANVEG) and a Lagrangian footprint model will be used to synthesize and interpret the data.

1.4 Revision date of this Document

2.0) INVESTIGATOR(S)

2.1) Investigator(s) Name And Title.
Collaborators and Technical Assistance:

Dr. Lianhong Gu, Dr. Liukang Xu, Mr. Ted Hehn, Ms Nancy Kiang, Ms Francesca Ponti

Informal Collaborative: Dr. Kevin Tu, Dr. Todd Dawson, Bill Frost

2.2) Contacts (For Data Acquisition and Production Information).

Dennis Baldocchi, Department of Environmental Science, Policy and Management, 151 Hilgard Hall University of California, Berkeley, CA 94720, Baldocchi@nature.berkeley.edu; 510-642-2874 (phone); 510-643-5098 (fax)

Scalar and energy flux data (e.g. CO\textsubscript{2}, water vapor, sensible heat and solar energy): Co-authorship if there is extensive use of the data to validate models. Acknowledgement if only few data are used to make a supporting point.

Meteorological data: Acknowledgment.

Acknowledgement: Field data obtained and prepared by Dennis Baldocchi, Liukang Xu and Lianhong Gu, Department of Environmental Science, Policy and Management, 151 Hilgard Hall University of California, Berkeley, CA 94720, Baldocchi@nature.berkeley.edu; 510-642-2874 (phone); 510-643-5098 (fax)

3. INTRODUCTION

3.1) Objective/Purpose.

The objective of this research is to measure and model air-surface exchange rates of water vapor, sensible heat and CO\textsubscript{2} over a grazed grassland and oak/grass savanna and to study the abiotic and biotic factors that control the fluxes of scalars in this landscape. Scalar flux densities were measured with tower-mounted measurement systems.

The work to be done addresses three overarching objectives. The first objective of the proposed work is:
to establish a new AmeriFlux site and measure and model the biotic and abiotic factors that govern carbon, water and energy exchange of a grassland and a grass/oak savanna over the time scales of hours to days and years.

The second objective of the proposed work is:

to study the impact of heterogeneous canopies and sloping terrain on the measurement and modeling of carbon and water fluxes across a gradient of canopies.

The third objective of the proposed work relates to flux footprints and the partitioning of fluxes between the vegetative and soil components. We intend to study:

a) the temporal and spatial patterns of soil respiration, evaporation, micrometeorology, canopy structure and energy exchange; b) use this information to parameterize a two dimensional and multi-layer footprint model; c) combine information on wind direction, flux footprints and biomass transects to evaluate the flux climatology of the site.

RESEARCH HYPOTHESES

Based on the science and objectives we have introduced and discussed, many interesting questions arise that can form the basis of this research project. Key questions we intend to address in relation to measuring and modeling carbon and water fluxes of a grassland and an oak/grass savanna. They relate to the functionality and variability of carbon and water vapor fluxes in time and space.

Questions relating to functionality include:

1) How do year-to-year variations in annual rainfall, due to the presence of El Niño or La Niña, affect the carbon and water balances of these systems?
2) How do the carbon and water vapor fluxes of an annual grassland differ from a nearby grass/oak savanna over a spectrum of time scales?
3) How does the mixed grass/tree landscape coordinate the use of water for the gain of carbon over the course time?

Along the vertical spatial axis, we intend to ask:

1) How do vertical differences in physiological capacity, plant architecture and the physical environment integrate to the canopy dimension?
2) What are the relative roles of soil and vegetation on mass and energy exchange?

The main hypotheses we intend to ask with regard to horizontal variability include:

1) Can a flux footprint model be used with a one-dimensional biophysical model to assess fluxes of water and carbon across a patchy landscape or must we consider the advection/diffusion equation in two dimensions?
2) How does sloping terrain affect the conventional measurement of eddy fluxes over short vegetation? Does CO₂ leak out of the control volume as air drains out of the system close to the ground?

3) What are the relative contributions of biodiversity (a mix of species and functional types) on land-atmosphere trace gas exchange? Can we assess this flux by integration information on wind direction, the flux footprint, the biomass distribution and how fluxes respond to climate?

4) How do trees modify the microclimate and ecophysiological functioning of nearby grass? Consequently, is it better for grass to grow under a tree, where it experiences less evaporative demand (but less rainfall) or out in the open, nearby?

With a gradient network in northern California and across to Tennessee, we intend to address:

1) How do spatial gradients in rainfall and temperature affect canopy leaf area, structure and functioning and biosphere-atmosphere trace gas exchange?

Critical questions relating to temporal variation include:

1) What are the relative contributions of dominant times scales (year, season, day, hour) that cause variations of canopy water and carbon exchange and how do these scales vary with climate and functional type?

2) How do seasonal changes in plant structure, soil moisture and physiological capacity affect annual net fluxes?

- 3.2) Summary of Variables.

Key measured flux variables solar radiation components (albedo, net radiation, incoming solar (near infrared + visible), quantum (visible)) and latent heat, sensible heat, soil heat and CO₂ flux densities above the canopy. Key meteorological and soil variables being measured included wind speed, wind direction, air temperature, relative humidity, soil temperature, CO₂ concentration. The micrometeorological measurements are supported with periodic measurements of photosynthetic capacity, stomatal conductance, soil respiration, leaf area index, plant height, carbon isotopes of air, soil and roots and pre-dawn water potential.

- 3.3) Discussion.

We are measuring eddy flux densities of CO₂, water vapor and sensible heat and turbulence statistics above a grazed grassland near Ione, CA. The site is flat, but is situated in topographically undulating and among the oak/grass savanna biome of eastern California, at the foot of the Sierra Nevada mountains. The forest stand was horizontally homogeneous throughout the area deemed as the flux footprint, a region extending over several hundred meters.

One eddy flux measurement system was mounted at 2 m above the ground. The eddy flux densities are determined by calculating the covariance between vertical velocity and scalar fluctuations (see Baldocchi
et al., 1988). Wind velocity and virtual temperature fluctuations were measured with identical three-
dimensional sonic anemometers. Our experience has also taught us that it is prudent to employ three-
dimensional sonic anemometers in forest meteorology applications. When deploying an anemometer
over vegetation it is nearly impossible to physically align the vertical velocity sensor normal to the mean
wind streamlines; sensor orientation problems typically arise due to sloping terrain and to the practice of
extending a long boom upwind from a tower. By deploying a three-dimensional anemometer, we are
able to make numerical coordinate rotations to align the vertical velocity measurement normal to the
mean wind streamlines. CO₂ and water vapor fluctuations were measured with an open-path, infrared
absorption gas analyzer, developed at by LICOR.

Fast response meteorology data were digitized, processed and stored using a microcomputer-controlled
system and in-house software. Digitization of sensor signals is performed with hardware on the sonic
anemometer. Sensor data are output at 10 Hz. Spectra and co-spectra computations show that these
sampling rates are adequate for measuring fluxes above and below forest canopies (Anderson et al.,
1986; Baldocchi and Meyers, 1991; Amiro, 1990a). Mass and energy flux covariances are be stored at
half-hour intervals. Instantaneous data was recorded continuously. Scalar fluctuations and flux
covariances are computed post experiment using Reynolds averaging over 30 minute periods. We also
apply despiking routines, as the new sonic anemometer and open path sensor spike several times per run.
Without spike removal, the flux covariances are very noisy

Proper interpretation of experimental results and model evaluation requires detailed ancillary
measurements of many environmental variables. Energy balance components that were measured
include the net radiation balance, soil heat flux and canopy heat storage

4.0) THEORY OF MEASUREMENTS

4.1 Micrometeorological Measurement Theory.

A client of mass and energy flux information want to know how much material is being transferred
across the land/air interface. Due to practical and theoretical circumstances micrometeorologists cannot
place their sensors directly at this interface. Instead, they must make measurements several meters
above the land surface and rely on the application of theories, which are derived from the conservation
equations of mass, momentum and energy to interpret fluxes made several meters above the underlying
surface. The equation defining the conservation of mass and energy provides the guiding principles for
designing and executing micrometerological experiments over land surfaces. Mathematically, this
equation can be derived by considering the mass flow of material in and out of a conceptual cube (u c).
By applying Reynolds decomposition to the velocity and scalar variables and then time averaging, this
equation is expressed, in tensor notation as:

\[
\frac{dc}{dt} = \frac{\partial c}{\partial t} + u_i \frac{\partial c}{\partial x_i} + c \frac{\partial u_i}{\partial x_i} - \frac{\partial u_i' c'}{\partial x_i} + S_g(t, x_i) + S_{cb}(t, x_i)
\] (1)
The total time rate of change of a scalar (dc/dt) is a function of its local time rate of change plus the advection of material across the lateral. These terms equal the flux divergence and source/sink strengths due to biology (S_b) and chemical reactions (S_c,h).

The terminology associated with tensor notations suggests the space, x_i and velocity, u_i variables are incremented from 1 to 3. For the space dimension this corresponds to the longitudinal (x), lateral (y) and vertical (z) dimensions. For velocity, this incrementing corresponds with u, v and w velocity vectors, at are aligned in the x, y and z spatial coordinates.

For the simple case of steady state conditions (dc/dt = 0), horizontal homogeniety (no horizontal gradients) and no chemical reactions, this equation reduces to:

\[ 0 = -\frac{\partial w' c'}{\partial z} + S_b(z) \] (2)

Integrating this equation with respect to height yields the classic relationship, from micrometeorological theory is generally applied. We obtain a relation that shows that the eddy covariance between vertical velocity and scalar concentration fluctuations (measured at a reference height, h) equals the net flux density of material in and out of the underlying soil and vegetation, or the net ecosystem exchange of CO\textsubscript{2} (N\textsubscript{e}).

\[ \bar{w'} c'(h) = \bar{w'} c'(0) + \int_0^h S_b(z) dz \] (3)

When the thermal stratification of the atmosphere is stable or turbulent mixing is weak, material leaving leaves and the soil may not the reference height h. Under such conditions the storage term becomes non-zero, so it must be added to the eddy covariance measurement if we expect to obtain a measure of material flowing into and out of the soil and vegetation.

\[ \bar{w'} c'(h) + \int_0^h \frac{\partial c}{\partial t} dt = \bar{w'} c'(0) + \int_0^h S_b(z,t) dz \] (4)

While the storage term is small over short crops, it is an important quantity over forests. With respect to CO\textsubscript{2}, its value is greatest near sunrise and sunset when there is a transition between respiration and photosynthesis and a break-up of the stable nocturnal boundary layer by the onset of convective turbulence. With respect to the study of pollutants, the interception of a wandering plume can cause the storage term to deviate from zero.

Advection effects can occur in complex terrain, where drainage flows can occur and across the border of different vegetation or vegetation and natural features such as rivers and lakes. Consideration of the case...
of advection is often difficult. For it is not straightforward when and which terms should be neglected. Recently, Lee (1998) evaluated the budget equation for CO$_2$ and arrived at the following equation.

\[
\int \int \int \left[ \frac{\partial}{\partial t} \bar{c} - \bar{w} \frac{\partial \bar{c}}{\partial z} + \frac{\partial}{\partial z} (\bar{c} \bar{w}) \right] dz = \int \bar{w}(h) \int_0^b \left( \frac{\partial}{\partial t} \bar{c} - \bar{w} \frac{\partial \bar{c}}{\partial z} + \frac{\partial}{\partial z} (\bar{c} \bar{w}) \right) dz + \int_0^b \bar{S}_b(z)dz
\]

In the case of Eq. 5, \(\bar{w}\) is a mean vertical velocity, which can be induced by mesoscale circulations or topographical drainage.

How can we apply the conservation equation to measure fluxes? In the field, we measure fluxes at a given height above the surface, but we want to know the rate CO$_2$ is taken up by the surface below. The vertical flux density of S will remain unchanged with height if the underlying surface is: 1) homogeneous and extends upwind for a considerable distance (this requirement ensures the development of a surface boundary layer); 2) if scalar concentrations are steady with time; and 3) if no chemical reactions are occurring between the surface and the measurement height.

Condition one can be met easily through proper site selection. As a rule of thumb the site should be flat and horizontally homogeneous for a distance between 75 and 100 times the measurement height (Monteith and Unsworth, 1990). Condition two is met often for many scalars. Non-steady conditions are most apt to occur during abrupt transitions between unstable and stable atmospheric thermal stratification, during the passage of a front or from the impaction of a plume from nearby power plants.

As we attempt to apply micrometerological conditions to over long, time periods and over non-ideal conditions, we must rely on a comprehensive form of the conservation of mass equation and design our experiment on the basis of the terms that need to be assess. For the work at Walker Branch Watershed, we have found that we need to assess Eq. 5 routinely to obtain defensible fluxes, such as respiration during the winter dormant period and large enough values at night that are consistent with the amount of biomass that is respiring.

4.2 Eddy Covariance Technique.

The eddy covariance method is a direct method for measuring flux densities of scalar compounds. The vertical flux density is proportional to the covariance between vertical wind velocity (w) and scalar concentration fluctuations (c).

A wide range of turbulent eddies contribute to the turbulent transfer of material. Proper implementation of Eq. 1 requires that we sample across this spectrum of eddies. In frequency domain, eddies contributing to turbulent transfer having periods between 0.5 and 2000s typically contribute to mass and energy exchange (Wesely et al. 1989). Hence, wind and chemical instrumentation must be capable of responding to high frequency fluctuations. And computer-controlled data acquisition systems must
sample the instrumentation frequently to avoid aliasing and average the signals over a sufficiently long period to capture all the contributions to the transfer.

On applying the covariance relation, it is assumed implicitly that the mean vertical flux density is perpendicular to the streamlines of the mean horizontal wind flow. Consequently, the mean vertical velocity, perpendicular to the streamlines of the mean wind flow, equals zero. In practice, non-zero vertical velocities occur due to instrument misalignment, sloping terrain and density fluctuations. These effects must be removed when processing the data, otherwise mean mass flow can introduce a bias error (see Businger, 1986; Baldocchi et al., 1988).

Evaluating the accuracy of the eddy correlation method is complicated. Factors contributing to instrument errors include time response of the sensor, signal to noise ratio, sensor separation distance, height of the measurement, and signal attenuation due to path averaging and sampling through a tube. Natural variability is due to non-steady conditions and surface inhomogeneities. Under ideal conditions natural variability exceeds about +/-10%, so it is desirable to design a system with an error approaching this metric.

Moore (1986) discusses transfer functions for sensor response time and separation distance. We preformed preliminary calculations of transfer function integrals. Corrections due to sensor time constants and separation are less than a few percent. Hence, we decided not to make transfer function to our flux measurements; our experimental design minimized the need for such corrections since we used an open path infrared gas analyzer and a sonic anemometer. Furthermore, these instruments were placed over a tall rough forest, so small distances in physical displacement have little impact on the measurement of scalar flux densities.
Figure 1 Transfer function of eddy fluxes for the current grassland configuration. Potential errors for moderate winds and stable conditions may reach 10% on the basis of Moore algorithms.

The sensors which are used to measure CO2 fluxes measure CO2 density fluctuations, rather than mixing ratio. Application of the density corrections, attributed to Webb et al. (1980) are applied to our measurements. Corrections to eddy fluxes will be greatest during periods with high sensible heat fluxes, as when the grass is dead and dormant.
5.0) EQUIPMENT

- 5.1) Instrument Description.

The experiment includes instrument setups for eddy covariance, meteorology and soil physical properties. The eddy Flux system involves measurements of turbulence, vertical, horizontal wind velocities and virtual temperature. The instruments include:

- Sonic anemometer: Gill Windmaster Pro,
- CO2 and water vapor concentrations: Licor-LI7500
- Meteorological Variables
  - PAR incoming: Kipp and Zonen PAR-Lite
  - PAR reflected: Kipp and Zonen PAR lite
  - Net radiometer: Kipp and Zonen
  - Pyranometer: Kipp and Zonen
Pressure: Vaisala
Temperature: Vaisala, HMP (sensor U3030042)
Relative humidity: Vaisala, HMP
Rain, Texas Electronics, tipping bucket, TE 5252mm (sensor LX 243734)

Soil variables include

Soil heat flux plates: Huseflux (3)
Soil temperature: UCB probes at 2, 4,8,16 and 32 cm (3)
Soil moisture: Theta probe ML2x, Delta-T Devices (5), 2 at 10 cm, 2 at 20 cm and 1 at surface

Eddy covariance flux measurements are made using a triple-axis wind master prof sonic anemometer and a Licor 7500 infrared absorption spectrometer. The sonic anemometer measured vertical (w) and horizontal (u,v) wind velocity and virtual air temperature (T). This anemometer model provides digital output at a rate of 10 Hz. The infrared absorption spectrometer measures water vapor and CO₂ density fluctuations. The sensor responds to frequencies up to 15 Hz, has low noise and high sensitivity (20 mg m⁻³ volt⁻¹). The sensor is rugged and experiences little drift over several weeks of continuous operation.

Soil heat flux density is measured by averaging the output of three soil heat flux plates (Huseflux). They are buried 0.01 m below the surface and were randomly placed within a few meters of the flux system. Soil temperature are measured with two multi-level thermocouple probes. Sensors are spaced logarithmically at 0.02, 0.04, 0.08, 0.16 and 0.32 m below the surface.

Photosynthetically active photon flux density, solar radiation and the net radiation balance are measured above the grassland with a quantum sensor (Kipp and Zonen PAR lite), pyranometer (Kipp and Zonen) and a net radiometer (Kipp and Zonen), respectively. A LICOR line sensor (modelxxx) is used to measure light through the grass.

Air temperature and relative humidity are measured with appropriate sensors (Vaisala, model HMP-35A).

Static pressure is measured with a Vaisala model PTB101B sensor. It operates on a 600 to 1060 mb range over 2.5 volts.

Ancillary meteorological and soil physics data are acquired and logged on a Campbell CR-23x and CR-10x data loggers. Half-hour averages were stored on a computer, to coincide with the flux measurements.

CO₂ concentration profiles are measured with the LICOR 7500.
5.1.1 Principles of Operation.

Sonic Anemometer:

Three-dimensional orthogonal wind velocities \((u,v \text{ and } w)\) and virtual temperature \((T_v)\) were measured with a sonic anemometer (Wind Master Pro). The pathlength between transducers was 0.15 m. The sensor software corrected for transducer shadowing effects (see Kaimal et al. 1990). Virtual temperature heat flux was converted to sensible heat flux using algorithms described by Kaimal and Gaynor (1991).

Infrared Absorption Spectrometer:

Water vapor and CO\(_2\) concentrations were measured with an open-path infrared absorption spectrometer.

Soil Heat Flux Transducer:

An encapsulated thermopile yields a voltage output proportional to the temperature difference across the top and bottom surfaces. The device has been calibrated in terms of heat flux through transducer corresponding to the observed temperature difference.

Instrument Measurement Geometry.

The eddy flux measurement system was placed at 2 m above the ground. The Licor 7500 was 0.15 m beside the sensor.

Power: solar panels

6 Siemens SP75 panels in parallel with Morningstar 30 regulator and 6 12 vdc batteries. System draw is 2.1 amps.

Manufacturer of Instrument.

Sonic anemometer:
Gill

Soil heat transducer:

HuseFlux
Figure 2

Net Radiometer:
Kipp and Zonen

Pyranometer and Quantum Sensors

Kipp and Zonen

Data logging system:

Campbell Scientific
P. O. Box 551,
Logan, UT 84321
CO2/water vapor analyzer

LI 7500

LICOR
4421 Superior St
Lincoln, NE

Temperature and humidity

Vaisala

Pressure Sensor

Static
Vaisala

Physiology

LI 6400
Licor

Soil respiration chamber

Pressure bomb
Eddy covariance flux measurements are made using a triple-axis wind master prof sonic anemometer and a Licor 7500 infrared absorption spectrometer. The sonic anemometer measured vertical (w) and horizontal (u,v) wind velocity and virtual air temperature (T). This anemometer model provides digital output at a rate of 10 Hz. The infrared absorption spectrometer measures water vapor and CO₂ density fluctuations. The sensor responds to frequencies up to 15 Hz, has low noise and high sensitivity (20 mg m⁻³ volt⁻¹). The sensor is rugged and experiences little drift over several weeks of continuous operation.

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Photosynthetically active photon flux density, solar radiation and the net radiation balance are measured above the grassland with a quantum sensor (Kipp and Zonen PAR lite), pyranometer (Kipp and Zonen) and a net radiometer (Kipp and Zonen), respectively. A LICOR line sensor (modelxxx) is used to measure light through the grass.

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Manufacturer of Instrument.

Sonic anemometer:
Gill

Soil heat transducer:
HuseFlux

Net Radiometer:
Kipp and Zonen

Pyranometer and Quantum Sensors
Kipp and Zonen

Data logging system:

Campbell Scientific
P. O. Box 551,
Logan, UT 84321

CO2 analyzer
LICOR
4421 Superior St
Lincoln, NE

Temperature and humidity
Vaisala

Pressure Sensor
Static
Vaisala

5.2) Calibration.

Flux and mean concentration CO2 analyzers were calibrated against secondary calibration gases. These gases were referenced to standards prepared by NOAA/CMDL (http://www.cmdl.noaa.gov/ccg/refgases.html)
Trace gas standards used for measuring CO2 by the Carbon Cycle Group (CCG) of NOAA CMDL are contained in aluminum cylinders purchased from Scott- Marrin, Riverside, California. The cylinders are treated with a proprietary passivation treatment. CCG uses three different size cylinders but most of our standards are contained in 30 liter (internal volume) cylinders. The cylinders are ordered with brass Ceodeux cylinder valves (CGA590) containing all-metal seats and nickel stems. The cylinders are shipped to CMDL with 1380 kPa (200 psig) of dry, ultrapure air. It is important for the cylinders to be dry (and remain dry) during filling and use. Brass cylinder valves rather than stainless steel, are recommended for all trace gas species measured by CCG.

The zero and span of the LICOR infrared gas analyzers were measured every day.

The water vapor sensor was calibrated against mixed air samples and referenced to data from a chilled mirror dew point hygrometer. Stability of the water vapor calibration was checked in the field by comparing the instrument sensitivity to the output of a Vaisala relative humidity sensor. The relative humidity sensor was new and calibrated by the manufacturer. We also compared the output of the Vaisala relative humidity sensor against a redundant dew point hygrometer. Both sensors yielded identical humidity measurements.

- 5.2.1) Specifications. Calibration factors.

Sonic anemometer: supplied by manufacturer. 1.0 m s\(^{-1}\)/V with sonic pathlength 0.15 m.

Carbon dioxide: about 30 mg m\(^{-3}\) volt\(^{-1}\).

Water vapor density fluctuations: varies with vapor density. 2.0 g m\(^{-3}\) volt\(^{-1}\) at 6 C and 3 g m\(^{-3}\) volt\(^{-1}\) at 14 C.

Soil heat transducer: about 40 W m\(^{-2}\) mv\(^{-1}\)

net radiation: 12 W m\(^{-2}\) mv\(^{-1}\)

quantum flux density: 180 µmol m\(^{-2}\) s\(^{-1}\) mv\(^{-1}\)

Pressure: 0.184 mb/mv

- 5.2.1.1) Tolerance. Precision or sensitivity estimates:

Solar and net radiation: 1 W m\(^{-2}\).

Air temperature fluctuations: 0.1 K.
Vertical wind velocity fluctuations: 0.01 m s\(^{-1}\).

Surface radiative temperature: 0.1 K.

Other Calibration Information.

CO\(_2\) gases were originally referenced to NIST standards. We have depleted those gases and recently purchased standards from Dr. Pieter Tans, CMDL/NOAA lab.

6.0) PROCEDURE

- 6.1) Data Acquisition Methods.

- 6.2) Spatial Characteristics.

- 6.2.1) Spatial Coverage.

Flux footprint calculations were done at our lab. We find that most of the flux sensed by our eddy covariance instrumentation comes from a region within 300 m of the tower.

The below canopy measurement of net radiation was performed with sensors on a tram that traversed a 30 m transect under the forest. This design was needed to account for high spatial heterogeneity of light near the floor of a forest.

- 6.2.2 Spatial Resolution.
- 6.3) Temporal Characteristics.

n/a

- 6.3.1) Temporal Coverage.

- 6.3.2) Temporal Resolution.

Flux data were sampled 10 times per second and averaged over 30 minutes. Times reported are the ending times of the averaging period. Fluctuations were computed by subtracting a running mean average (determined with a digital recursive filter using a 400 s time constant) from instantaneous values.

7.0) OBSERVATIONS/ SITE CHARACTERISTICS

- 7.1) Field Notes.
The field site is located on the near Ione, CA on the property of Mr. Fran Vaira. The latitude is: 38° 24.400 N; the longitude is: 120° 57.044 W; and the altitude is: 129 m (see USGS 7.5' Quadrangle: Irish Hill, Calif.Sections 26, 27, 34, 35)

A picture of the site and instrumentation is shown below.
A. Site Characteristics

The site is a grazed grassland opening in a region of oak/grass woodland. The landscape has been managed, as the local ranchers have removed brush and cattle graze the herbs. The main grass and herb species include bromus, frescue, oat, medusa head, rose clover. This an annual and seasonal grassland. The active growing season is between November and May.
Soils

In formation on soils come from the Soil Survey of Amador Area, California, 1965, USDA. The soil is of the Auburn-Exchequer association. It is a very shallow to moderately deep rocky or gravely soil in material from metabasic rocks and metasedimentary slate and schist (Soil Survey of Amador Area, California, 1965, USDA, Soil Conservation Service)

Classified as AsD, Auburn extremely rocky silt loam, 3 to 31 percent slopes. The profile is:
*0-9 inches, strong brown silt loam, Massive. Hard when dry, friable when wet slightly acid
*14 inches plus, weathered, very pale brown

capability units Vis-4 (18) range site 2.

Soil Texture

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<th>Date Sampled: 4/28/01; Vaira Ranch</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
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</tr>
<tr>
<td>Clay</td>
<td>30</td>
<td>57</td>
<td>13</td>
</tr>
</tbody>
</table>

The soil bulk density is 1.43 +/- 0.125 g cm\(^{-3}\), based on 27 samples from 5 to 30 cm

Soil Chemistry

N 0.14% and C was 1.39%.

Climate and Weather

There is no long term weather records at the site, but weather records from are available from the NCDC cooperative network for Ione, from 1959-1977 (t about 38.35°N 120.93°W. Height about 85m / 278 feet above sea level)

Ione
**Average Rainfall**

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
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<td>mm</td>
<td>99.6</td>
<td>83.9</td>
<td>76.8</td>
<td>51.9</td>
<td>10.7</td>
<td>3.1</td>
<td>0.3</td>
<td>5.2</td>
<td>5.5</td>
<td>31.6</td>
<td>94.5</td>
<td>94.6</td>
<td>558.7</td>
</tr>
<tr>
<td>inches</td>
<td>3.9</td>
<td>3.3</td>
<td>3.0</td>
<td>2.0</td>
<td>0.4</td>
<td>0.1</td>
<td>0.0</td>
<td>0.2</td>
<td>0.2</td>
<td>1.2</td>
<td>3.7</td>
<td>3.7</td>
<td>22.0</td>
</tr>
</tbody>
</table>

**Source:** derived from [NCDC Cooperative Stations](#). 16 complete years between 1959 and 1977 a near by station, Ben Bolt, recorded.

Using interpolation calculations of regional climate data using MtCLIME (Peter Thorton, Univ Montana) we estimate that a 30 year mean of precipitation is about 611 mm. The mean maximum temperature is 24.35 C.

Camp Pardee has temperature data. It is at about the same elevation, but south of the field site.

**CAMP PARDEE, CALAVERAS COUNTY, CALIFORNIA USA**

Located at about 38.25°N 120.86°W. Height about 200m / 656 feet above sea level.

**Average Temperature**

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>7.3</td>
<td>10.0</td>
<td>11.6</td>
<td>14.5</td>
<td>18.5</td>
<td>22.6</td>
<td>25.8</td>
<td>25.1</td>
<td>22.6</td>
<td>18.3</td>
<td>12.1</td>
<td>7.8</td>
<td>16.3</td>
</tr>
<tr>
<td>°F</td>
<td>45.1</td>
<td>50.0</td>
<td>52.9</td>
<td>58.1</td>
<td>65.3</td>
<td>72.7</td>
<td>78.4</td>
<td>77.2</td>
<td>72.7</td>
<td>64.9</td>
<td>53.8</td>
<td>46.0</td>
<td>61.3</td>
</tr>
</tbody>
</table>

**Source:** derived from [NCDC TD 9641 Clim 81 1961-1990 Normals](#). 30 years between 1961 and 1990.

For current weather conditions, weather maps and forecasts, see [Weather Site dot com](#).

**CAMP PARDEE, CALAVERAS COUNTY, CALIFORNIA USA**

Located at about 38.25°N 120.86°W. Height about 200m / 656 feet above sea level.

**Average Rainfall**

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>97.8</td>
<td>88.2</td>
<td>91.6</td>
<td>49.0</td>
<td>18.5</td>
<td>5.9</td>
<td>1.2</td>
<td>1.6</td>
<td>8.5</td>
<td>29.5</td>
<td>65.5</td>
<td>85.4</td>
<td>543.7</td>
</tr>
<tr>
<td>inches</td>
<td>3.9</td>
<td>3.5</td>
<td>3.6</td>
<td>1.9</td>
<td>0.7</td>
<td>0.2</td>
<td>0.0</td>
<td>0.1</td>
<td>0.3</td>
<td>1.2</td>
<td>2.6</td>
<td>3.4</td>
<td>21.4</td>
</tr>
</tbody>
</table>

**Source:** 8.0) DATA DESCRIPTION

Bill Frost Production data
95-96 Total production 4992 lbs/acre
96-97 late December 48 lbs/acre, total production 2621 lbs/acre
97-98 late December 88 lbs/acre, late February 1555 lbs/acre, total 
production 4547 lbs/acre
98-99 late December 579 lbs/acre, early March 1555 lbs/acre, total 
production 3552 lbs/acre
99-00 late December 582 lbs/acre, total production 2784 lbs/acre
00-01 late December 819 lbs/acre, early March 1434 lbs/acre, total 
production 3824 lbs/acre

Most common species this year were:

Soft Chess Bromus mollis
Medusahead Taeniatherum asperum
Foxtail fescus Vulpia megalura
Rose clover Trifolium hirtum

'30 min data for AmeriFlux Web Page

File names:

Grassland2000.dat

These data are subject to several data filters. Filtout searches for outliers and replaces them with 9999. 
These periods are associated with rain events for the most part. Outliers are defined by limits set for 
variables according to variance, skewness and kurtosis thresholds. They differ for the sonic anemometer 
and infrared spectrometer. Filtturb is a filter that screens the data for limits according to Monin Obukov 
scaling theory. Mostly it looks for limits on the standard deviation of w. FiltCO2 screens the CO2 flux 
data for physiological limits.

Data variables in grassland2000.dat files

/* Headers for output files */

daytime_, " DAYTIME");
nee_, " NEE umol m-2 s-1");
fcwpl2d_, " FC_WPL_2D umol m-2 s-1");
wc2d_, " WC_2D umol m-2 s-1");
wc1d_, " WC_1D umol m-2 s-1";
fclid_, " FC WPL 1D umol m-2 s-1";
fcadd_," CO2 Storage umol m-2 s-1";
co2ppm_, " CO2 LI7500 ppm");
rhoc_, " RHOC mmol m-3";
cvolt_, " C volt");
cc_, " CO2 var");
skc_, " skewness CO2";
krc_, " kurtosis CO2";

rnet_, " Rnet Net Radiation W m-2";
solar_, " Solar Radiation W m-2";
parup_, " incoming PAR umol m-2 s-1";
pardown_, " Par reflected umol m-2 s-1";
paralbedo_, " PAR albedo ");

wnddir_," Wind Direction degrees";
wndspd_, " Wind Velocity m s-1";
ustar_," Friction Velocity m s-1";
w_," wbar m s-1";
ww_, " w var");
angw_, " ang of w rotation");
sigw_ustar_, " std dev w/ u* ");
krw_, " kurtosis w");
zoverl_, " z over L");

leflx_," LE Latent Heat Flux W m-2");
rhoq_, " RHOQ mmol m-3");
qvolt_, " q volt");
qq_, " q var");
skq_, " skewness q");
krq_, " kurtosis q");

hflx_," H Sensible Heat Flux W m-2";
tsonic_, " Tsonic");
ttsonic_, " T sonic var");
skt_," skewness Tsonic");
krtsonic_, " kurtosis Tsonic");

parfl_," PAR floor umol m-2 s-1";
tair_," Tair C";
rhov_," absolute humidity mol m-3");
vpd_," Vapor pressure deficit kPa");
presskpa_," Pressure kPa");
precip_," precipitation mm");
wetness_," wetness ");
9.0) DATA MANIPULATIONS

9.1) Formulas.

Subroutine that computes covariances and applies gas law corrections

    static void process_flux()
    {
        float lambda, lfusion, rhoadry, rhomoist, tk, tksonic, cpair, rhovkg,
            spechum, sig;
        float wbarwp1, e_wpl_2d, e_wpl_1d, le1d, ewpl;
        float hflxid, wtguess, wtguess_1d;
        float wqq, wqq1d, wtcorr1d, wtcorr2d;
        float term1, term2, terma, termb, sig16;
        float w_rhov_g_2d, w_rhov_g_1d, rhov_g;
        float rhoc_mg_m3;

        wtcorr2d=0;
        wtguess=0;

        wtcorr1d=0;
        wtguess_1d=0;

        tk=out.tair+273.15;
        tksonic=out.tsonic+273.15;

        if(fabs(out.tair)>50)
{ 
  tk=tksonic;
  out.tair=out.tsonic;
}

/* latent heat of evaporation and fusion */

lambda = 3149000 - 2370 * tk; /* MJ kg-1 */
lfusion = 334000. ;

if (tk < 273) 
  lambda += lfusion; 

lambda /= 1000.; /* J g-1 */

/* density of dry air */

rhoadry = (out.presskpa - out.ea) * 28.964 / (8.314 * tk); /* kg m-3 */

/* density of moist air */

rhomoint = (out.presskpa * 28.964 / (8.314 * tk)) * (1. - .378 * out.ea / out.presskpa); /* kg m-3 */

/* Weight Cpair according to moist and dry air densities */

rhovkg=out.rhov*18.0/1000.; /* absolute moisture densisty, kg m-3, converted from mol m-3 */

cpair = 1010. * rhoadry + 4182. * rhovkg; /* specific heat of moist air */

spechum = rhovkg / rhomoint; /* specific humidity, relative to moist air, kg/kg */

sig = rhovkg / rhoadry; /* specific humidity relative to dry air, kg/kg */

/* Compute WPL corrected sensible heat and latent heat flux densities: */
correct virtual temperature heat flux from sonic to actual heat flux. It is a function of the specific moisture flux density, which in turn is a function of the sensible heat flux. Since neither is known a priori we must iterate.

/*
do {
    wtguess=wtcorr2d;
    wtguess_1d=wtcorr1d;

    /*
    Webb et al correction for evaporation flux density
    \[ E_{wpl} = w'rhov' (1 + (rhov/rhoa)(ma/mv)) + rhov w'T'/T \quad (g \cdot m^{-2} \cdot s^{-1}) \]

    Make sure the units are correct. The WPL correction was derived from the gas law:
    \[ \frac{\rho_a}{ma} + \frac{\rho_v}{mv} = \frac{P}{RT}, \]
    where \(\rho_a\) and \(\rho_v\) have units of mass/m\(^3\)
    */
    rhov_g=rhovkg*1000.;    /* absolute density of water vapor, g m\(^{-3}\) */

    /* convert molar flux density to mass flux density to apply WPL correction to evaporative flux densities */
    w_rhov_g_2d=out.w_rhov_2d*18./1000.;        /* g m^{-2} s^{-1}, evaporative flux density, 2 d rotation */
    w_rhov_g_1d=out.w_rhov_1d*18./1000.;        /* g m^{-2} s^{-1}, evaporative flux density, 1 d rotation */

    e_wpl_2d = (1. + sig * 1.607) * w_rhov_g_2d + rhov_g * wtguess / tk;    /* g m^{-2} s^{-1} */
    e_wpl_1d = (1. + sig * 1.607) * w_rhov_g_1d + rhov_g * wtguess_1d / tk;    /* g m^{-2} s^{-1} */

    /*
divide factor of 1000 is needed to change $e_{wpl}$ from g m$^2$ s$^{-1}$ to kg m$^{-2}$ s$^{-1}$, so units cancel when divided by $\rho_{amoist}$ (kg m$^{-3}$)

```
/*
  wqq = $e_{wpl \_2d}$ * (1. - spechum) / (1000. * $\rho_{a\_moist}$); /* m s$^{-1}$ */
  wqq1d = $e_{wpl \_1d}$ * (1. - spechum) / (1000. * $\rho_{a\_moist}$); /* m s$^{-1}$ */
*/

Correct the sonic virtual heat flux and convert it to a true thermodynamic sensible heat flux covariance, as adjusted for moisture flux

```
/*
  wtcorr2d = (out.wt2d - .51 * tk * wqq) / (1. + .51 * spechum) ; /* K m s$^{-1}$ */
  wtcorr1d = (out.wt1d - .51 * tk * wqq1d)/ (1. + .51 * spechum) ; /* K m s$^{-1}$ */
}while(fabs((wtcorr2d-wtguess)/wtcorr2d) > 0.01);

```
/* Sensible heat flux with 2-D rotation */
out.hflx = wtcorr2d * $c_{pair}$; /* W m$^{-2}$ */

```
/* Sensible heat flux with 1-D rotation */
hflx1d = wtcorr1d * $c_{pair}$; /* W m$^{-2}$ */

```
/* Latent heat flux with 2-D rotation */
out.leflx = $\lambda$ * $e_{wpl \_2d}$; /* W m$^{-2}$ */

```
/* Latent heat flux with 1-D rotation */
le1d = $\lambda$ * $e_{wpl \_1d}$; /* W m$^{-2}$ */

```
if (in.wx2d[3] == 9999)
{
```
CO2 fluxes, Webb et al. density corrections

The new Licor LI-7500 measures mole density. I need to convert to mass density, then apply wpl corrections

```
out.co2ppm = out.rhoc * 28.96 / rhoadry; /* CO2 conc ppm */

sig16 = sig * 1.6077; /* (ma/mv)(rhov/rhoa) */

wbarwpl = 1.6077 * w_rhov_g_2d / (1000.* rhoudry) + (1. + sig16) * wcorr2d / tk; /* m s-1 */

rhoc_mg_m3 = out.rhoc * 44.; /* convert mol density of CO2 to mass density */

term1 = 1.6077 * w_rhov_g_2d * rhoc_mg_m3 / (1000.* rhoadry); /* mg CO2 m-2 s-1 */

term2 = (1. + sig16) * rhoc_mg_m3 * wcorr2d / tk; /* mg CO2 m-2 s-1 */
```
termb = (1. + sig16) * rhoc_mg_m3 * wtcor1d / tk; /* mg CO2 m-2 s-1 */

if (wtcorr2d == 9999)
term1 = 9999;

if(w_rhov_g_2d == 9999)
term2 = 9999;

/* WPL Correction */
if((term1 != 9999) && (term2 != 9999) && (out.wc2d != 9999))
{
    /* 2d CO2 Flux */
    out.fc_wpl_2d = out.wc2d + 1000. * (term1 + term2)/44.; /* micromol m-2 s-1 */

    /* 1d CO2 flux */
    out.fc_wpl_1d = out.wc1d + 1000. * (terma + termb)/44.; /* micromol m-2 s-1 */
}
else
{
    out.fc_wpl_2d = 9999;
    out.fc_wpl_1d = 9999;
}

if (in.wx2d[5]==9999)
{
    out.fc_wpl_2d = 9999;
    out.fc_wpl_1d = 9999;
}

return;
/* end of process flux */
}

- 9.1.1 Derivation Techniques/Algorithms.

    none provided.

- 9.2) Data Processing Sequence.
Flux covariances are computed in the field by the data acquisition program. Back at home, calibrations are double and triple checked by comparing old and new calibrations and by comparing the mean response of the scalar flux sensors against independent meteorological instruments. Tests are made for energy balance closure to ensure that the data are of reliable quality. Programs are then run to delete periods when the sensors were off line, off range, being maintained or un-reliable due to rain or instrument malfunction.

- 9.2.1 Processing Steps and Data Sets.

- 9.2.2 Processing Changes.

  None to report.

- 9.3 Calculations.

- 9.3.1 Special Corrections/Adjustments.

  Eddy fluctuations:

- 9.4) Graphs and Plots.

  None.

10.0) ERRORS

- 10.1) Sources of Error.

- 10.2) Quality Assessment.

Surface energy balance is tested by comparing measurements of available energy against the sum of latent and sensible heat flux.
- 10.2.1) Data Validation by Source.

- 10.2.2 Confidence Level/Accuracy Judgement.

The following are the best estimates of accuracy for a single flux estimate:

- Net radiation: +/- 4 to 7%
- Soil heat flux: +/- 10%
- Latent heat flux: +/- 15 to 20% or +/- 30 W m^-2, whichever is larger
Sensible heat flux $\pm 15$ to $20\%$ or $\pm 30$ W m$^2$, which ever is larger

None of these estimates addresses the variability of flux estimates from site to site.

Detection limit of CO2 flux system: 0.025 mg m$^{-2}$ s$^{-1}$

The intermittency of turbulence limits the sampling error of turbulent fluxes to 10 to 20%. On top of this we have to deal with measurement errors. Fortunately, lots of statistically averaging reveals stable fluxes and small bias errors ($< 12\%$) on the surface energy fluxes.

CO2 concentrations $\pm 5 – 10$ ppm, the zero drift is causing problems. David Earle of University of Nebraska computed that potential error in CO2 based on published specs could be $\pm 30$ ppm!!!

- 10.2.3 Measurement Error for Parameters and Variables.

11.0) NOTES

- 11.1) Known Problems With The Data.

PAR sensor had problems in 2000. We had to recalibrate it against another sensor.

Rain data was missing until Feb 2001

Sonic anemometer had signal loss in Dec, 2000

Soil moisture sensors were out between Day 45 and 60, 2001. Lightening killed multiplexor

LICOR spikes. We are despiking data with post processing routine. If more than 100 spikes per 30 minutes (out of 18000 samples) then we reject those data

Sonic occasional spikes

There is poor relation between sonic temperature and virtual temperature. We are investigating this issue

Soil sensors need final calibration.

Due to solar power, we are not running temperature aspirator until more solar energy is available or until we have converted our 0.5 amp aspirator to a 0.1 amp unit.
11.2) Usage Guidance.

Prior to application of the advection correction we would caution

CAUTION should be exercised when using flux data for several hours surrounding dawn and dusk since
these are periods of unsteady conditions. In addition, nighttime data should be closely scrutinized. There
are periods when CO2 may be draining out from below the instruments.

With use of the advection correction, we caution that schemes are under development. Fluxes may need
to be updated as we learn more about the physics of the problem and re-fine our correction procedure.
At present we compute new sensor orientation functions every time we move the sonic anemometer.

12.0) REFERENCES

Publications Generated From this Project

15.0) GLOSSARY OF ACRONYMS

16.0 Need to add climate data, wind rose information, soil properties, plant properties, species
information and percentages

Acknowledgements

Ranch Owner
Mr and Mrs Fran Vaira
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Jackson, CA  95642
209) 223-0646

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US Dept of Energy, Terrestrial Carbon Program, Roger Dahlman administrator
California Agricultural Experiment Station

Contribution to
AmeriFlux and Fluxnet programs