Energy Balance and Closure of a Typical Winter Wheat Agroecosystem in the North China Plain: Postprint

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Abstract

Accurate quantitative analysis of material and energy exchange between land and atmosphere is crucial for water resources management and sustainable agricultural development. Energy balance closure is an important evaluation index for assessing the accuracy of observational data and analyzing surface energy balance. In this study, continuous observations of energy fluxes and conventional meteorological elements were conducted during 2013–2014 in a typical winter wheat farmland ecosystem in the North China Plain using an open-path eddy covariance system and an automatic weather station measuring all elements. The diurnal and annual variation characteristics of various energy fluxes in the winter wheat farmland were analyzed, and energy closure and Bowen ratio were calculated for four growth stages (emergence stage, overwintering stage, jointing stage, and grain-filling stage). The results showed that: on a diurnal scale, the diurnal variation trends of net radiation and various energy components for the selected four growth stages all exhibited unimodal quadratic curves; peak values of net radiation, sensible heat flux, and latent heat flux occurred between 12:00–13:00, while peak values of soil heat flux occurred between 14:00–15:00. On an annual scale, the variation trends of net radiation and latent heat flux were relatively consistent, both reaching minimum values of 114.51 W • m ² and 13.47 W • m ² during the overwintering stage, and maximum values of 327.02 W • m ² and 116.56 W • m ² during the grain-filling stage. The representative observation dates selected for the four growth stages exhibited good energy closure, with energy closure rates of 0.49, 0.77, 0.81, and 0.76, respectively. The diurnal variation trends of Bowen ratio values within the four growth stages all showed an inverted "U" shape; the Bowen ratio during the emergence stage reached a maximum value of 2.12 at 14:00, while the overwintering, jointing, and grain-filling stages reached maximum values around 10:00, being 1.48, 0.31, and 0.58, respectively. The quantified results of this study can provide a basis

for research on water and heat fluxes in farmland ecosystems of the North China Plain.

Full Text

Energy Balance and Closure of a Typical Winter Wheat Farmland Ecosystem in the North China Plain

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Abstract

Accurate quantification of energy and mass exchange between terrestrial ecosystems and the atmosphere is crucial for water resource management and sustainable agricultural development. Energy balance closure serves as a vital index for evaluating observation data accuracy and analyzing surface energy balance. This study employed an open-path eddy covariance system and an automatic weather station to conduct continuous observations of energy fluxes and conventional meteorological elements in a typical winter wheat farmland ecosystem in the North China Plain during 2013–2014. We analyzed the diurnal and annual variation characteristics of energy fluxes, and calculated energy closure and Bowen ratio across four growth stages (seeding, overwintering, jointing, and grain-filling). Results showed that at the diurnal scale, net radiation and energy components exhibited unimodal quadratic curves across all four stages, with peak values of net radiation, sensible heat flux, and latent heat flux occurring between 12:00–13:00, while soil heat flux peaked at 14:00–15:00. At the annual scale, net radiation and latent heat flux showed consistent trends, reaching minimum values during the overwintering stage (114.51 W • m ^{2} and 13.47 W • m ^{2}, respectively) and maximum values during the grain-filling stage (327.02 W • m ^{2} and 116.56 W • m ^{2}, respectively). Energy closure was satisfactory on representative observation dates for the four growth stages, with closure ratios of 0.49, 0.77, 0.81, and 0.76, respectively. Diurnal variation of Bowen ratio displayed an inverted U-shaped pattern across all stages, reaching a maximum of 2.12 at 14:00 during the seeding stage, and maxima of 1.48, 0.31, and 0.58 around 10:00 during the overwintering, jointing, and grain-filling stages, respectively. These quantitative results provide a basis for research on water and heat fluxes in farmland ecosystems of the North China Plain.

Keywords: Winter wheat; Farmland ecosystem; Energy balance characteristics; Eddy covariance system; Energy closure ratio; North China Plain

1.1 Study Area Description

Winter wheat cultivation in the North China Plain has a long history with continuous planting areas and large-scale production. This experiment was conducted at the Fengqiu Agro-Ecological Experimental Station of the Chinese Academy of Sciences (hereafter referred to as the Fengqiu Station), a key field research base for agriculture, resources, ecology, and environmental studies in the North China Plain. The station serves as a critical site in the Chinese Ecosystem Research Network (CERN) and a national key field observation station. Fengqiu County features a semi-arid, semi-humid warm temperate continental monsoon climate with an annual mean temperature of 14.2°C, annual precipitation of 605 mm, annual evaporation of 1875 mm, and a frost-free period of 214 days. The region is rich in light and heat resources, with flat terrain at an elevation of 67 m. The Yellow River borders the county to the east and south, providing relatively abundant water resources. The southern area forms back-river depressions due to Yellow River seepage, while the northern part connects to the hinterland of the North China Plain. Soils are primarily yellow fluvo-aquic soils developed from Yellow River sediments, with secondary woody shrubs and grasses as the main natural vegetation. The dominant cropping system is a winter wheat-maize rotation. Drought, waterlogging, salinization, and wind-sand are the main factors affecting local crops. This study conducted continuous field observations from October 23, 2013 (winter wheat sowing) to June 5, 2014 (harvest), spanning nine months.

1.2.1 Eddy Covariance System Observations

The experimental field at Fengqiu Station represents a typical farmland ecosystem with flat terrain, uniform soil texture, and a single cropping structure, meeting the requirements for upwind fetch length. The open-path eddy covariance system consisted of a WindMaster Pro three-dimensional ultrasonic anemometer (Gill Instruments, UK; wind speed range: 0–0.65 m · s^{1}, accuracy: <1.5% RMS @ 12 m · s^{1}, resolution: 0.01 m · s^{1}) and an LI-7500A CO /H O fast-response infrared gas analyzer (LI-COR, USA; CO calibration range: 0–3000 µmol · mol^{1}, H O calibration range: 0–60 mmol · mol^{1}). The system automatically measured and stored instantaneous fluctuations of three-dimensional wind speed, temperature, H O, and CO in the near-surface layer during surface-atmosphere interactions, calculating sensible heat flux (H) and latent heat flux (LE). Raw data were sampled at 10 Hz, with 30-minute averages output. The eddy covariance system was installed at a height of 4.45 m.

1.2.2 Comprehensive Meteorological Observations

A comprehensive meteorological observation system at Fengqiu Station monitored long-term environmental variables, including: DYNAMET air temperature/relative humidity sensors (at 100 cm and 300 cm heights), DYNAMET wind speed/direction sensors, DYNAMET precipitation sensors, DYNAMET solar radiation sensors, NR01-05 four-component net radiometers, TM-L20 soil temperature sensors (at 10 cm, 20 cm, and 30 cm depths), EC-5 soil moisture sensors (at 10 cm, 20 cm, and 30 cm depths), and HFP01-10 soil heat flux plates installed on the east, west, and north sides of the observation tower. All sensors were connected to a CR1000 data logger (Campbell Scientific, USA) with 30-minute data output intervals.

1.2.3 Data Preprocessing

Due to adverse weather conditions, human factors, and instrument malfunctions, collected data contained outliers requiring quality analysis and correction before further research. Processing steps included: outlier removal, double coordinate rotation correction, density correction (WPL), and sonic virtual temperature correction. Strict quality control standards were applied to filter abnormal data: (1) observations exceeding five times the mean of adjacent values, (2) data during rainfall events, and (3) nighttime periods with weak turbulence (friction velocity $u^* < 0.15$ m · s ^{1}). Missing or rejected flux values were gap-filled using linear interpolation for short gaps (<1 day) or data from similar weather conditions on adjacent days. For extended periods of severe weather or equipment failure (>1 day), gap-filling followed the mean diurnal variation method.

1.2.4 Energy Closure Evaluation Method

Based on the first law of thermodynamics, the surface energy balance equation can be expressed as:

$$\mathrm{LE} + H = R_n - G - S - Q \tag{1}$$

where LE is latent heat flux, H is sensible heat flux, R_n is net radiation, G is soil heat flux, S is canopy heat storage (generally 5% of net radiation), and Q represents other energy sources that can be neglected for farmland ecosystems within observational precision limits. Thus, equation (1) simplifies to:

$$\mathrm{LE} + H = R_n - G \tag{2}$$

The left side represents standard turbulent fluxes, while the right side represents available energy. Energy balance ratio (EBR), the most commonly used method for analyzing energy closure, is calculated by dividing turbulent fluxes by available energy over an observation period:

$$\mathrm{EBR} = \frac{\mathrm{LE} + H}{R_n - G} \tag{3}$$

Under ideal conditions ignoring canopy heat storage, available energy approximates standard turbulent fluxes, with higher EBR values indicating greater accuracy of eddy covariance observations. Causes of energy imbalance include measurement scale mismatch, extreme weather impacts, and instrumental systematic errors.

1.2.5 Bowen Ratio-Energy Balance Method

The Bowen ratio-energy balance method (BREB) expresses the ratio of sensible to latent heat flux ( ) as:

$$\beta = \frac{H}{\mathrm{LE}} = \frac{K_h \cdot \Delta\theta / \Delta Z}{K_w \cdot \Delta q / \Delta Z} \tag{4}$$

where K_h and K_w are turbulent exchange coefficients for heat and water vapor, $\Delta\theta$ and Δq are potential temperature and humidity differences between two observation heights, ΔZ is the height difference, ρ_a is air density (kg · m ^{3}), C_p is specific heat capacity (1.004 kJ · kg ^{1} · K ^{1}), and L is latent heat of vaporization (2505.4 kJ · kg ^{1}).

Based on Monin-Obukhov similarity theory assuming equal exchange coefficients ($K_h = K_w$), the equation simplifies to:

$$\beta = \gamma \cdot \frac{\Delta T}{\Delta e} \tag{5}$$

where γ is the psychrometric constant and P is actual atmospheric pressure (hPa). In this study, measured temperature difference ΔT replaced potential temperature difference $\Delta\theta$, with Δe representing water vapor pressure difference between two heights (hPa).

Bowen ratio calculation accuracy depends primarily on values. During sunrise and sunset when $R_n - G$ approaches zero, or during precipitation when temperature and vapor pressure gradients oppose each other, approaches -1, yielding large errors. Following Perez et al. [30] and considering instrument precision and vapor pressure gradient measurements, anomalous values were identified when:

$$\beta = \frac{R_n - G}{\mathrm{LE}(1 + 1/\beta)} \tag{6}$$

where Δe is water vapor pressure difference between two heights (hPa).

2.1.1 Diurnal Variation Characteristics of Energy Fluxes

Driven by solar radiation energy, farmland ecosystems undergo energy flow, material synthesis and transfer, and carbon-water cycling processes. Heterogeneity in underlying surface types and community structures leads to differences in evapotranspiration and heat conduction capacities. Consequently, energy fluxes exhibit distinct allocation patterns after net radiation enters the ecosystem [31].

Clear days were selected as representative periods within each of the four winter wheat growth stages (seeding, overwintering, jointing, and grain-filling) for comparative flux data analysis.

As shown in [Figure 1: see original paper], diurnal variations of fluxes across the four stages displayed unimodal quadratic curves, with all energy components based on net radiation energy, which correlates with sunshine duration and intensity. During the seeding stage, net radiation became positive at 8:00, peaked at 330.92 W · m ^{2} at 12:00, and turned negative after 16:30. In the overwintering stage, net radiation turned positive at 9:00, reached a maximum of 259.32 W · m ^{2} at 12:30, and became negative after 16:30. The jointing stage showed positive net radiation from 7:30, peaking at 559.26 W · m ^{2} at 12:30, and turning negative after 18:00. During the grain-filling stage, net radiation became positive at 5:30 (the earliest sunrise among all stages due to the sun’ s proximity to the Tropic of Cancer), reaching a maximum of 702.22 W · m ^{2} at 13:00. Thus, net radiation maxima occurred during the grain-filling stage and minima during the overwintering stage, typically between 12:00–13:00.

Latent heat flux (LE) diurnal variation closely matched net radiation (R_n) with a unimodal quadratic curve, while sensible heat flux (H) showed an opposite trend. As winter wheat developed and canopy coverage increased, LE increased while H decreased. During the seeding stage, LE exceeded H before 10:00 but was lower than H between 10:00–16:00, indicating weak crop transpiration due to low canopy coverage, with most net radiation energy used for surface-atmosphere heat exchange. The overwintering stage showed similar patterns, though LE briefly exceeded H during 13:00–14:00, likely due to irrigation effects. During jointing and grain-filling stages, LE was significantly greater than H during daytime, with canopy coverage reaching maximum and transpiration/soil evaporation becoming strongest. In the grain-filling stage, LE peaked at 404.27 W · m ^{2} at 11:30, while H reached its maximum of 185.37 W · m ^{2} at 14:00.

Soil heat flux (G), representing heat transfer due to uneven soil temperature distribution, was relatively small compared to other energy components in equation (2) and remained essentially balanced over longer periods [32]. As shown in [Figure 1: see original paper], G was negative at night across all stages (heat transfer from deep soil to surface) and positive during daytime (heat transfer from surface to deep soil). The magnitude of G variation ranked as: jointing > grain-filling > seeding > overwintering. G maxima generally occurred at 14:00–15:00, lagging net radiation peaks by 1–2 hours, particularly evident during jointing and grain-filling stages due to soil heat capacity differences from air requiring time for energy transmission. The maximum G value of 53.20 W · m ^{2} occurred during the jointing stage.

2.1.2 Annual Variation Characteristics of Energy Fluxes

[Figure 2: see original paper] illustrates annual variation trends of net radiation and energy components during the 2013–2014 winter wheat growing season. Before harvest in June, net radiation (R_n) and latent heat flux (LE) showed consistent trends with similar magnitudes, both reaching minimum values during the overwintering stage. The annual minimum average values were 114.51 W · m ^{2} for R_n and 13.47 W · m ^{2} for LE, while sensible heat flux (H) remained relatively high at 33.61 W · m ^{2} and soil heat flux (G) was 13.05 W · m ^{2}, accounting for 26.59% and 10.32% of available energy, respectively. This pattern resulted from weak winter solar radiation, low vegetation coverage, large exposed soil areas, and occasional snow cover, which increased surface albedo and directed more available energy toward atmospheric and vegetation heating, yielding smaller R_n and LE but larger H.

After the overwintering stage, R_n and LE increased as solar incidence angles grew larger, days lengthened, and temperatures rose, promoting rapid winter wheat growth, increased canopy coverage, and enhanced transpiration and evaporation. Following the overwintering stage, winter wheat entered the regreening and jointing stages, where H and LE showed an overall negative correlation. LE peaked in May at 116.56 W · m ^{2} while R_n reached 327.02 W · m ^{2}, with LE comprising 35.64% of available energy. H and G accounted for smaller proportions at 20.01% and 7.87%, respectively.

After June, mature winter wheat was harvested. R_n decreased to 317.79 W · m ^{2} compared to May, likely due to increased rainfall and overcast conditions. LE declined to 49.11 W · m ^{2} because post-harvest canopy coverage dropped sharply, reducing transpiration and making LE primarily soil evaporation consumption. H increased rapidly to its maximum of 128.12 W · m ^{2}, with G at 34.05 W · m ^{2}, as most available energy heated the atmosphere and soil over the largely bare surface.

2.2 Energy Closure Analysis of Winter Wheat Farmland Ecosystem

Energy balance method, calculating the energy balance ratio, is the primary approach for assessing eddy covariance data reliability. Without considering diurnal differences, we examined closure by regressing the sum of sensible and latent heat fluxes (H + LE) against available energy ($R_n - G$) across the seeding, overwintering, jointing, and grain-filling stages. As shown in [Figure 3: see original paper], regression slopes for the four stages were 0.49, 0.77, 0.81, and 0.76, respectively, with correlation coefficients of 0.91, 0.92, 0.96, and 0.97. This indicates satisfactory energy closure across all stages, superior to results from other winter wheat studies [33-35] and studies on different underlying surfaces [36-38], demonstrating reliable eddy covariance flux data for the North China Plain winter wheat farmland ecosystem.

2.3 Bowen Ratio Analysis of Winter Wheat Farmland Ecosystem

As shown in [Figure 4: see original paper], Bowen ratio variations on typical dates during seeding, overwintering, jointing, and grain-filling stages all exhibited inverted U-shaped patterns. Daytime Bowen ratios remained relatively stable with minimal variation, primarily because calm or light wind conditions during daytime prevented horizontal airflow from affecting temperature and humidity gradients, yielding accurate calculations under positive temperature and humidity conditions. Under stable nocturnal atmospheric stratification, Bowen ratios became negative with large fluctuations and numerous outliers. Diurnal variations showed greater fluctuations during early morning and evening hours across all stages, when LE and H exhibited abnormal fluctuations and errors in available energy calculations caused larger flux calculation errors, consistent with findings by Liu et al. [39] and Wang et al. [40].

Bowen ratio was influenced by sunrise/sunset times, net radiation energy, and extreme weather (rainfall and strong winds). During the seeding stage, Bowen ratio became positive at 9:00, peaked at 2.12 at 14:00 (maximum H proportion of R_n), and turned negative after 19:00. In the overwintering stage, Bowen ratio became positive at 10:00 (due to later sunrise and smaller R_n), peaked at 1.48 at 11:00, and turned negative after 17:00, consistent with H diurnal variation. During the jointing stage, Bowen ratio became positive at 9:00, peaking at 0.31 at 11:00, because increased canopy coverage made LE dominate R_n with H daily means lower than LE, matching energy component diurnal patterns. In the grain-filling stage, Bowen ratio turned positive at 7:00 (earliest sunrise with maximum annual R_n energy), peaking at 0.58 at 9:00 when H reached its maximum proportion of R_n, consistent with grain-filling stage H variation.

3 Discussion and Conclusions

Energy imbalance has long been ubiquitous across ecosystem flux observations, with an average closure deficit of 20% [24-25, 41]. Eddy covariance methods assume homogeneous underlying surfaces and horizontally uniform near-surface airflow. Liu et al. [35] demonstrated significant seasonal characteristics in energy closure rates for winter wheat/summer maize rotation fields in the North China Plain. In this study, energy closure rates were 0.48, 0.73, 0.83, and 0.76 for seeding, overwintering, jointing, and grain-filling stages, respectively, with lower closure during seeding and higher during jointing. This aligns with Wilson et al. [24] regarding better closure during growing seasons than non-growing seasons. At the entire growth period scale, the maximum closure rate of 0.83 occurred during jointing, similar to results from wheat-rice rotation fields [42] and winter wheat studies [43]. Energy closure rates increased from seeding to jointing stages, consistent with Li et al. [25] showing better summer closure improving from winter to summer across ChinaFLUX sites. The maximum closure rate of 0.83 in this study compares with 0.83 in a Jinzhou maize ecosystem [32], findings from Guo et al. [44] in North China Plain maize ecosystems, and results from Twine et al. [41] and Wilson et al. [24].

Based on existing research [40] and site conditions, energy imbalance causes can be summarized as: (1) Eddy instrument systematic bias, including inaccurate calibration, improper data processing, and extreme weather effects, requiring regular calibration and timely maintenance to reduce errors. (2) Observation source area scale mismatch between eddy covariance flux footprints and net radiometer/soil heat flux plate footprints, reducing turbulent-to-available energy ratios. (3) Neglected energy residual terms, particularly canopy heat storage and other energy sources, significantly impacting closure. Tian et al. [42] found higher closure rates over bare land than wheat or rice fields, indicating non-negligible canopy heat storage even for crops below 1 m height. (4) Unaccounted soil surface heat storage, as this study's soil heat flux calculations omitted surface heat storage values.

Energy closure rates are typically lower under complex conditions such as heterogeneous underlying surfaces and stable atmospheric stratification. Recent concepts of flux "area averaging" and simplified treatment methods offer significant guidance for energy balance research. Large eddy simulation (LES) still faces limitations in boundary layer turbulence applications [22]. Future research should develop new data processing methods to obtain area-averaged or more spatially representative flux results as effective solutions for eddy covariance energy closure problems.

This study analyzed diurnal and annual variation characteristics of water and heat fluxes in a typical North China Plain winter wheat farmland ecosystem using 2013–2014 eddy covariance and meteorological data. We examined energy closure on representative dates across four growth stages and calculated corresponding Bowen ratios. Key findings include: (1) At diurnal scales, net radiation and energy components showed unimodal quadratic curves correlating with sunshine duration and intensity across all stages, with peaks of net radiation, sensible heat flux, and latent heat flux at 12:00–13:00 and soil heat flux at 14:00–15:00, lagging by 1–2 hours. (2) At annual scales, net radiation and latent heat flux reached minima during overwintering (114.51 W · m ^{2} and 13.47 W · m ^{2}, respectively) while sensible heat flux peaked at 33.61 W · m ^{2} and soil heat flux at 13.05 W · m ^{2}; maxima occurred during jointing (327.02 W · m ^{2} and 116.56 W · m ^{2} for net radiation and latent heat flux, respectively). Net radiation and latent heat flux showed consistent trends, as did sensible and soil heat fluxes. (3) Energy closure was lower during seeding but satisfactory during overwintering, jointing, and grain-filling stages, with an average closure rate of 0.7, consistent with domestic and international studies. Bowen ratio peaked at 2.12 at 14:00 during seeding and around 10:00 during other stages. These quantitative results provide a foundation for water and heat flux research in North China Plain farmland ecosystems.

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