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Effects of the conversion of marshland to cropland on water and energy exchanges in northeastern China

Xiaosong Zhao ^a, Yao Huang ^{a,*}, Zhijun Jia ^a, Huizhi Liu ^a, Tao Song ^a,
Yuesi Wang ^a, Liqing Shi ^a, Changchun Song ^b, Yiyong Wang ^b

^a LAPC, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China

^b Northeast Institute of Geography and Agricultural Ecology, Chinese Academy of Sciences, Jilin 130012, China

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Summary To study the effect of land use change from marshland to croplands (rice and soybean cultivation), the water and energy fluxes in marshland, rice and soybeans were measured in northeastern China by the eddy covariance method for two growing seasons (May–October in 2005 and 2006). The rice (flooded until early September) and soybean (dry land) croplands were reclaimed from marshlands over 15 years ago. The annual precipitation in 2005 (480 mm) was below the 1981–2004 average (564 ± 130 mm), the precipitation in 2006 (655 mm) was significantly above average. The conversion of marshland to rice cropland resulted in an enhancement in latent heat flux (LE) and a decrease in sensible heat flux (H), which caused an increase in the ratio of LE and net radiation (LE/Rn) from 0.6 to 0.8 on average, and a decrease in H/Rn from 0.4 to 0.2 on average for the growing season. However, where the marshland was converted to soybean cropland, the latent heat flux was lower in 2005 under dry conditions, but higher in 2006 under wet conditions than it had been previously been, which was the opposite of the trend of H. Therefore, LE/Rn for soybean dropped to about 0.2 in the dry month of June 2005, and rose to 0.7 in the wet month of June 2006. H/Rn for soybeans shows opposite variation in LE/Rn in both years. The maximum evapotranspiration (ET) was about 4.5, 6–7 and 5 mm day⁻¹ for marshland, rice and soybeans, respectively. Rn, air temperature (Ta), vapor pressure deficit (VPD) and leaf area index (LAI) were important environmental and biological factors controlling the seasonal dynamics of LE and H for the three ecosystems, which explains about 80% of LE and 50% of H for marshland and rice; and 30–50% of LE and 60% of H for soybeans. Among them, Rn was the primary variable controlling the variations of LE and H for marshland and rice. However, for soybeans, VPD played a more important role in LE under dry conditions.

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* Corresponding author. Tel.: +86 010 8207 4294.
E-mail address: huangy@mail.iap.ac.cn (Y. Huang).

Introduction

Among the components of global change, land use change has the greatest impact on terrestrial ecosystems, profoundly altering land cover, biota and biogeochemical cycles (Walker, 2004). Historically, the most important change of land use was the expansion of agriculture (Houghton, 1999). Over the last three centuries, roughly 1200 Mha of forests and woodlands have been cleared; grasslands and pastures have diminished by about 560 Mha; and cropland areas have increased by 1200 Mha (Lambin et al., 2003; Ramankutty and Foley, 1999). In the United States, cropland increased from about 0.25 Mha in 1700 to 236 Mha in 1990. In the United States, the total area of forests and woodlands declined by 160 Mha (38%) as a result of agricultural clearing (Houghton and Hackler, 2000). In Europe, about 22% of forests or woodlands and about 34% of grasslands have been converted to cropland. Changes in land use from forest and grassland in China were 34% and 13%, respectively (Ramankutty and Foley, 1999).

Energy exchange is among the most important processes in terrestrial ecosystems because it affects variables such as temperature, water transport, plant growth and productivity (Dennison and Berry, 1989). The main components of surface energy balance are the net radiation, the heat stored in water and soil, the sensible heat flux, and the latent heat flux (or evapotranspiration). Evapotranspiration (ET) in vegetated wetlands is frequently the largest consumer of incoming energy (Drexler et al., 2004) and has a great influence not only on energy partition, but also on water conditions (e.g. temperature, depth and salinity) (Burba et al., 1999b).

The effects of land use change on water and energy fluxes have been reported over the last two decades. Land use change may impact watershed hydrology and regional climate by altering the land–atmosphere exchanges of energy and water (Bridgham et al., 1999; Giambelluca et al., 2000; Mahmood, 2005). These alterations to hydrology and energy partition have important implications for local and regional biogeochemical cycles and energy budgets (Priante et al., 2004). Conversion of pasture to rice cultivation in the eastern Amazon strongly affected both diurnal rates of turbulent exchange and the pattern of seasonal variation. These changes were accompanied by modified net radiation flux and turbulent heat flux and evaporation rates (Sakai et al., 2004). Deforestation decreased the rate of evaporation (including transpiration) (Giambelluca et al., 2000; Sen et al., 2004). However, evaporation rates in agricultural sites that had been abandoned for 25 years in Thailand were enhanced by positive sensible energy advection from nearby cultivated areas, and were similar to those of primary forest (Giambelluca et al., 2000). Irrigated agricultural land converted from forest in California increased latent heat flux and decreased sensible heat flux during the April–October dry season (Kueppers et al., 2006). However, few studies have focused on the effects of land use change from marshland to agriculture on energy fluxes.

In addition to the effects on water and energy fluxes, the conversion of forest, pasture and wetland to agriculture affected regional carbon budget that is associated with climate change. In a meta analysis of 74 publications, results

indicated that soil C stocks decline after land use changes from pasture to plantation (–10%), native forest to crop (–42%), and pasture to crop (–59%) (Guo and Gifford, 2002). Euliss et al. (2006) also estimated that agricultural conversion has resulted in the average loss of 10.1 Mg ha^{–1} of soil organic carbon for over 16 Mha of the North American prairie wetlands, and that wetland restoration has the potential to offset 2.4% of the annual fossil CO₂ emission reported for North America in 1990. The annual CO₂ balance for a peat–pasture ecosystem in New Zealand was 45 kg Cha^{–1} yr^{–1} (a source of CO₂), whereas peatland was a small sink of CO₂ (Nieveen et al., 2005).

The acreage of wetland in China is 65.94 Mha excluding rivers and ponds, accounting for approximately 10% of the world total (Liu and Ma, 2000). The Sanjiang Plain, located in northeast China, was formerly the largest marshland complex. However, to feed the growing populations over the last 50 years areas of marshland have been converted to agricultural. The area of marshland in this region has decreased from 5.34 Mha in the early 1950s to 0.84 Mha in 2000 (Liu and Ma, 2000). Approximately 84% of the marshland was lost due to agricultural conversion. Efforts have been made to evaluate the effects of agricultural conversion on soil temperature (Song et al., 2005), soil microbiological properties (Zhang et al., 2007a), soil organic carbon (Zhang et al., 2007b), and CH₄ emission (Wang et al., 2002) in this region, while less attention was paid to the effects on water and energy exchange.

During the growing seasons of 2005 and 2006, water and energy fluxes were measured with the eddy covariance system and related equipment in plots of marshland, rice, and soybeans. The main objectives of this paper are to evaluate the effects of agricultural conversion from marshland on latent heat flux and sensible heat flux, and on the partitioning of available energy into latent and sensible heat fluxes.

Materials and methods

Site description

The Sanjiang Plain is located at latitudes between 45°01'N and 48°28'N and longitudes between 130°13'E and 135°05'E, in northeastern China. The altitude is 55.4–57.9 m. The mean annual temperature is 1.9 °C with an average frost-free period of 125 d. The coldest month occurred in January with –21.6 °C and the warmest in July with 21.5 °C (1981–2004 average). Mean annual precipitation is about 560 mm with approximately 80% occurring in the plant growing season from May to October. The research site was established around the Sanjiang experimental station (47°35'N, 133°31'E) at the Chinese Academy of Sciences. The marshland, which belongs to the herbage marsh category, is continuously inundated and the dominant vegetation is *Carex lasiocarpa*; other subsidiary species include *Carex pseudocuraica* and *Glyceria spiculosa*. Soils are classified as Hydric Medihemists with a silty clay texture (Zhang et al., 2007a). Agricultural conversion of marshland to irrigated rice and dryland soybeans is a prevalent practice in this region. Plants in the marshland burgeon during the last ten days of May and defoliate in mid-October. The rice was continuously flooded with 4–8 cm of water until

early September. Table 1 shows the developmental stage of cropland and fertilization information.

The soybean site was converted from marshland more than 15 years ago. The rice site was converted a few years ago after soybean cultivation. The field areas are approximately 105 ha for marshland, thousands of hectares for rice and 10 ha for soybeans. The rice and soybean towers are approximately 1.5 km west and 500 m north of the marshland, respectively. Three towers with eddy covariance system were established in the middle of the marshland, rice and soybeans. The prevalent wind directions are SE and SW in this region. The upwind fetch in SE and SW is more than 200 m for soybean and more than 500 m for marshland and rice.

Flux measurements

Latent (LE) and sensible heat fluxes (H) were measured by the eddy covariance (EC) technique at a level of 2.5 m in marshland, rice and soybeans from May to October 2005 and 2006. The EC system consisted of a tri-axial sonic anemometer (CAST3, Campbell Scientific, USA) and a fast response open-path CO₂/H₂O infrared gas analyzer (Li-7500, LiCor Inc., USA). The spatial separation distance between the mid-points of these two neighboring sensors was about 15 cm to minimize underestimation of fluxes (Lee and Black, 1994). The two sensors were oriented toward the prevailing wind direction. All signals for the sensors were recorded at a sampling rate of 10 Hz and were averaged over 30 min periods. Planar fit rotation was applied (Wilczak et al., 2001). Water vapor flux from the EC system was corrected for the effects of air density fluctuations (Webb et al., 1980). Additionally, the temperature and humidity sensors (HMP45C, Vaisala, Helsinki, Finland) located 2.5 m above ground were also mounted on the flux tower. The half-hourly mean temperature and humidity were recorded by a CR23X datalogger (Campbell Scientific, Logan, UT, USA).

Micrometeorological and ancillary measurements

A micrometeorological system was operated at a 8 m tower, 10 m northwest of the flux tower in the rice. Air humidity and temperature (HMP45C, Vaisala, Helsinki, Finland), and wind speed (A100R, Vector Instruments, Denbighshire, UK) were measured at three heights (2 m, 4 m and 8 m). Air pressure (CS105, Vaisala, Helsinki, Finland) and wind direction (W200P, Vector Instruments, Denbighshire, UK) were measured at 2 m and 8 m, respectively. Precipitation

(RainGauge 52203, Young, Traverse City, MI, USA) was collected on the ground. Soil temperatures (107-L, Campbell Scientific Ltd., Edmonton, Alberta, Canada), water temperatures (Thermocouples, TT-T-24, Omega, USA) and soil water content (CS615, Campbell Scientific Ltd., Edmonton, Alberta, Canada) were monitored adjacent to the micrometeorological tower. Soil temperatures were measured at depths of 0.05, 0.1, 0.2, 0.4 and 0.8 m. Water temperatures sensors were set at the water surface, at a depth of 0.05 m below the water surface, and at the soil surface. The temperature sensor at the water's surface was kept afloat by inserting it into a piece of foam. The soil water contents were measured at depths of 0.05, 0.2 and 0.4 m. Soil heat flux (G) was determined by two soil heat flux transducers (HFP01SC, Hukseflux Inc.) placed 5 cm below the soil surface in two separate locations, 3 m away from the micrometeorological tower.

Net radiation (Rn) and photosynthetically active photon flux density (PPFD) were observed at a height of 2 m above the ground using a quantum sensor (LI190SB, Li-cor Inc., Lincoln, NE, USA) and a four-component net radiometer (CNR-1, Kipp & Zonen, Netherlands). All micrometeorological and soil data were recorded at half-hour intervals with a data logger (CR10X, Campbell Scientific).

Above ground biomass and leaf area index (LAI) were sampled within a radius of 250 m around the measuring plots every ten days from early May to late October in 2005 and 2006. However, there was a lack of above ground biomass for marshland and rice in 2005 and of LAI for rice in 2005. The plant samples were cut at ground level in three randomly placed areas of 0.5 m × 0.5 m for marshland, and 0.5 m in a row for soybean (distance of row was 0.65 m) and rice (distance of row was 0.37 m). LAI was measured with an LAI meter (LAI-2000, Li-Cor Inc., Lincoln, NE, USA).

Data processing

System performance was assessed by examining the degree of closure of the surface energy balance (Wilson et al., 2002). Energy balance closure of measured fluxes was calculated for rice by comparing the turbulent fluxes (LE + H) with the available energy (Rn - G - S), where S was the soil heat storage between the surface and a depth of 5 cm, water heat storage above ground was calculated by water temperature profiles (Gao et al., 2003). The slope of the regression line for half-hourly fluxes is 0.83 with a correlation coefficient of 0.76. That was similar to what has been reported for other sites, indicating good system performance (Wilson et al., 2002).

Table 1 The developmental stage of crops and fertilization information

Developmental stage of soybean	Day of year, 2005/2006	Fertilizer rate N-P ₂ O ₅ -K ₂ O (kg ha ⁻¹)	Developmental stage of rice	Day of year, 2005/2006	Fertilizer rate N-P ₂ O ₅ -K ₂ O (kg ha ⁻¹)
Before sowing		40-90-15	Before transplanting		23-50-45
Sowing	145/137		Transplanting	146/144	
Emergence	154/145		Turning green	153/147	26-0-0
Anthesis	188/186		Heading	209/207	23-0-15
Maturity	255/251		Maturity	253/251	
Harvest	271/277		Harvest	266/275	

The footprint was calculated with the FSAM model (Schmid, 1994), which was the numerical solution of the general diffusion equation. The analysis with a footprint model indicated that a footprint in the prevalent wind direction extended to about 90–140 m during the day, to about 120–200 m during calm conditions at night, which represented 80% of total flux. The footprints of other directions were similar to that of the prevailing direction. The footprints indicated that eddy covariance measurements for day and night were mainly influenced by the surface patch inside the field of interest.

Data rejection and gap filling

The eddy covariance (EC) data were usually screened for anomalous values outside the range normally encountered. A possible cause for such values is sensor malfunction due to interference from fog and birds. Breaks in data collection were caused by rain events, sensor maintenance, power failure, etc. Less than 20% of the data obtained from EC systems at the three ecosystems over the two years was discarded (except 30% of soybean data in 2006), which was lower than the average flux gaps reported for many other EC flux sites (Baldocchi et al., 2001; Wilson et al., 2002).

For calculation of daily and annual sums of the fluxes, these gaps were filled following the strategy suggested (Falge et al., 2001): (1) linear interpolation was used to fill the gaps that were less than 2 h and (2) other data gaps were filled using empirical relationships (look-up table method). In look-up tables, the LE and H data were binned by variables of Rn and vapor pressure deficit (VPD), so that a missing value with similar meteorological conditions could be "looked up". The look-up tables were assigned by monthly periods. The Rn classes consisted of 100 W m^{-2} intervals from -200 to 800 W m^{-2} . Similarly, VPD classes were defined through 0.1 kPa intervals, ranging from 0 to 3.2 kPa. Gaps in the look-up tables (classes with no mean assigned) were linearly interpolated. The method requires complete sets of Rn and VPD. Fortunately, there were no gaps for Rn. In three ecosystems, the VPD from other systems could be used to fill in the gaps because there were no significant differences in VPD in the three ecosystems. Gaps in precipitation were filled by data from a nearby weather station.

Data analyses involving relationships between latent heat flux (LE) and sensible heat flux (H) and environmental variables used 'good days' only. A good day was considered any day with 36 or more 30 min periods of measured LE and H data, with the missing 30 min gaps filled as outlined above. For other analyses (e.g. daily and monthly variations), a complete record of gap-filled LE and H data was used.

Result and discussion

Environmental factor variation

Fig. 1 shows main daily environmental variables based on the micrometeorological system. The daily mean air temperature (Ta) during measuring periods (from May to October) ranged from 1.4 to 25.4 °C and -3.9 to 26.6 °C in 2005 and 2006, respectively (Fig. 1a). The maximum Ta oc-

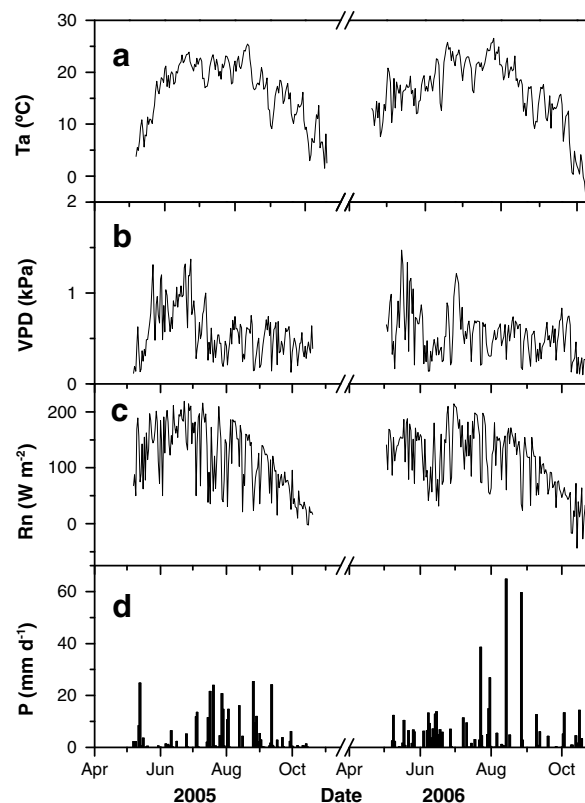


Figure 1 Mean daily micrometeorological conditions during May–October in 2005 and 2006: (a) air temperature (Ta), (b) vapor pressure deficit (VPD), (c) net radiation (Rn), and (d) precipitation (P).

curred in August. The daily mean vapor pressure deficit (VPD) exceeded 0.8 kPa before early July, and its value was below 0.8 kPa in the following period in both years (except that it was low in mid-June 2006 due to frequent rainfall) (Fig. 1b). The fluctuation of Rn (Fig. 1c) clearly indicated frequent cloudy conditions throughout the growing season. The low Rn occurred during a period in mid-July of 2005 and mid-June and mid-July of 2006, due to continually cloudy and rainy days.

Annual precipitation (P) in 2005 (480 mm) was below the 1981–2004 mean (\pm SD, 564 ± 130 mm), whereas it was above average in 2006 (655 mm). Total precipitation from May to October was 361 and 566 mm in 2005 and 2006, respectively (Fig. 1d). The maximum monthly precipitation in 2005 occurred in July (136 mm), and the maximum in 2006 occurred in August (200 mm). It is worth mentioning that monthly total precipitation in June 2005 (17.9 mm) was only one-third of the 23-year average (66.4 mm), and that rainfall in June 2006 (120 mm) was about twice the 23-year average.

Plant growth and development

The marshland growth period (about 130 days) was longer than the rice and soybeans (Fig. 2). Although leaf area index (LAI) and above ground biomass were higher in marshland than croplands before early July, they were highest and second highest for rice and soybean in the following periods.

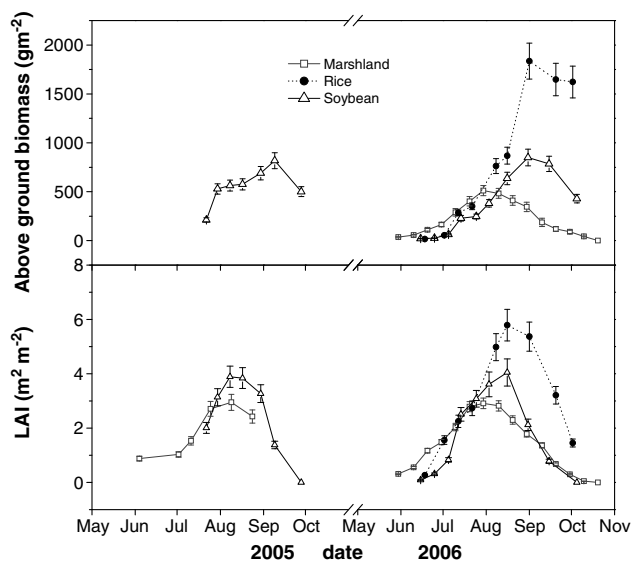


Figure 2 Seasonal variation of leaf area index (LAI) and above ground biomass during 2005 and 2006.

The maximum LAI occurred in mid-August for soybean and rice and early-August for marshland (Table 2). The date of maximum marshland biomass was consistent with the date of maximum LAI. For rice and soybeans, the date of maximum biomass lagged behind the date of maximum LAI. Fig. 2 shows seasonal variation of LAI and above ground biomass at the three ecosystems in 2005 and 2006.

Effects of land use change on water and energy exchange

Seasonal variations of LE showed obvious differences for marshland, rice and soybeans in both years (Fig. 3a). The daily LE value for rice was higher than for marshland and soybeans in both years, especially before mid-July, due to high LAI, high above ground biomass (Fig. 2, Table 2) and water covering the rice. Similar results were also reported in California, where land use changes occurred from forest to irrigated agricultural land (Kueppers et al., 2006), although biomass decreased at that site. The daily LE value in soybean was lower than in marshland before July in 2005, as low soil water content was limited in dry land under low precipitation in 2005 (480 mm), but was higher than in marshland in 2006 due to plentiful precipitation (655 mm) and higher above ground biomass for soybean (Figs. 1c and 2).

The low values of LE occurred in mid-July 2005 and June and July 2006 for the three ecosystems because of the abun-

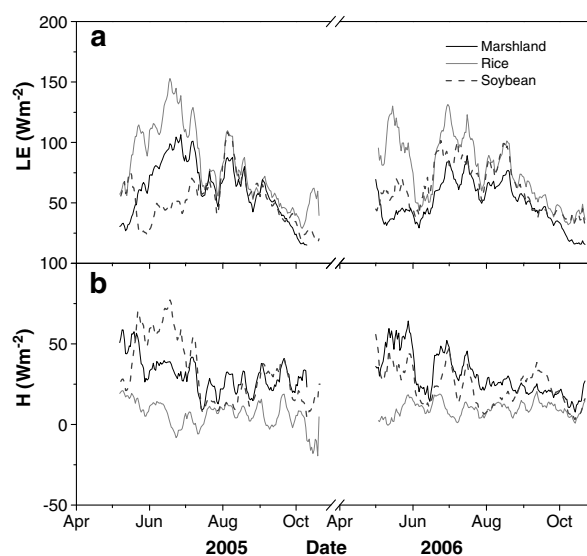


Figure 3 Seasonal distributions of (a) 7-day running average latent heat flux (LE) and (b) sensible heat flux (H) for marshland, rice and soybeans from May to October in 2005 and 2006.

dance of cloudy and rainy days in those periods. In addition, the higher value of daily LE was observed in early May for soybean (Fig. 3a) under plentiful precipitation conditions when the soybean seeds had not yet burgeoned (Fig. 1d).

The variations of H for marshland and soybeans were generally consistent (Fig. 3b). The high value of H for marshland and soybean occurred before mid-July, and then remained at a low value until the end of the growing season in 2005. However, the seasonal variation in H for rice was weaker than that for marshland and soybeans.

Effect of land use change on evapotranspiration (ET)

Monthly total evapotranspirations (ETs) for the three ecosystems show significant differences in both years (Fig. 4). In both 2005 and 2006, the monthly ET for rice was higher than marshland and soybean. In addition, the monthly ET for marshland was higher than for soybean in most months of 2005 under dry conditions. The contrary result was observed in 2006 under wet conditions. The maximum monthly ET occurred in June 2005 for marshland (93 mm) and rice (133 mm), though precipitation in June was only 18 mm. The same phenomenon was not observed in 2006, when precipitation was higher than average.

The monthly total ET for soybean has a good correlation with monthly precipitation in 2005 and 2006 (Fig. 5). The

	Marshland	Rice	Soybean
Maximum above ground biomass period	Early August	Early September	Late August
Maximum LAI period	Early August	Mid-August	Mid-August
Maximum plant height (\pm SD) (cm)	40 \pm 2	95 \pm 3	110 \pm 3
Maximum above ground biomass(\pm SD) ($g\ m^{-2}$)	512 \pm 20	1835 \pm 100	850 \pm 50
Maximum LAI (\pm SD) ($m^2\ m^{-2}$)	2.95 \pm 0.2	5.8 \pm 0.5	4.1 \pm 0.3

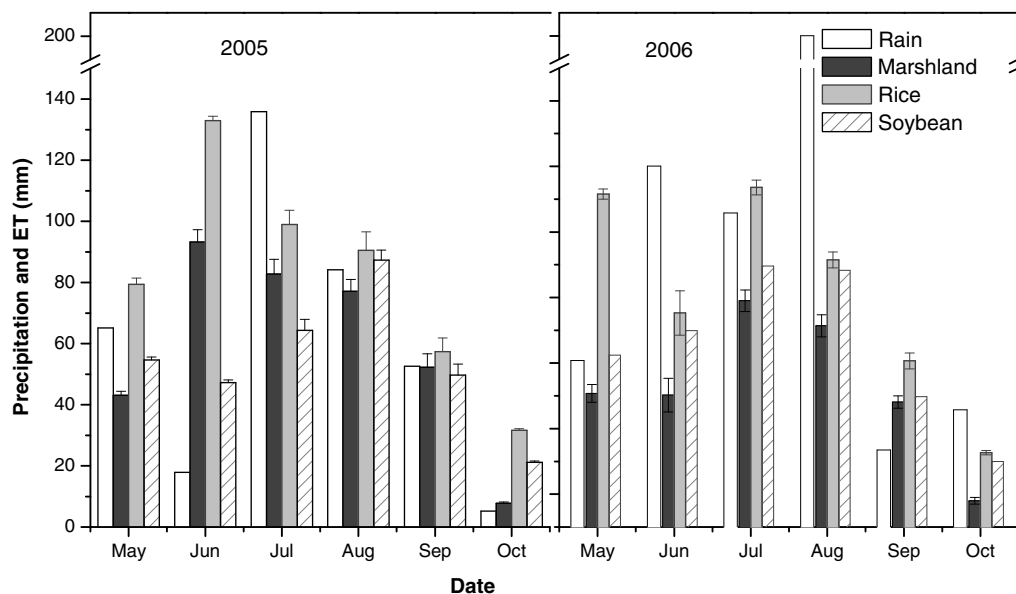


Figure 4 Monthly total precipitation and monthly total evapotranspiration (ET) with error bar (\pm SD) for marshland, rice and soybeans during the growing season in 2005 and 2006.

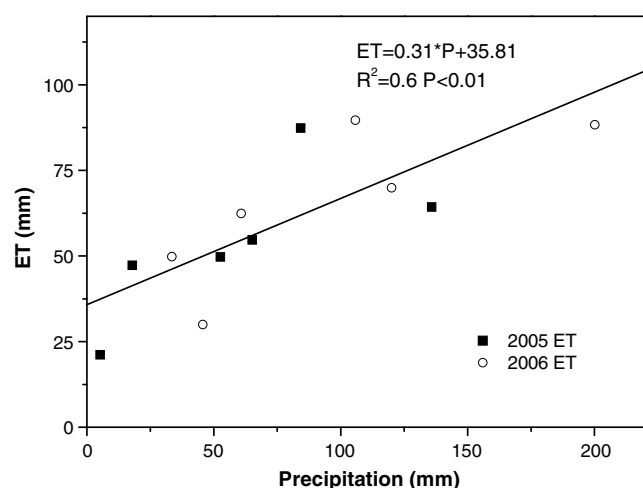


Figure 5 The relationship between monthly total precipitation (P) and ET at soybean in 2005 and 2006.

slope was 0.31 and R^2 was 0.6. This situation was not found in marshland and rice (figure not shown).

The total ET and ratio of ET/P for the growing season of 2005 and 2006 for the three ecosystems are shown in Table 3. The ratios of ET/P for marshland were 1.01 and 0.56 in 2005 and 2006, respectively. These were similar to the ratio of ET/P at Mer Bleue bog (the ratio of ET/P ranged from 0.75 to 0.98, with an average of 0.83) from 1998 to 2002 (Lafleur et al., 2005).

Clear differences in ET rates were found for three ecosystems in both years (Table 3). The mean ET rates were 2.19 and 1.84 mm day⁻¹ for marshland in 2005 and 2006, with a maximum ET of 4.5 mm day⁻¹. Similar ET rates were reported in other wetlands, including 2.2 mm day⁻¹ (with a 4.5 mm day⁻¹ maximum ET rate) at bog in Labrador (Price and Maloney, 1994), and 2.2–3.3 mm day⁻¹ (with a 4–

5 mm day⁻¹ maximum ET) at Mer Bleue bog in Eastern Ontario (Lafleur et al., 2005). The mean ET rate for rice converted from pasture in the Amazon was 2.7 \pm 1.2 mm day⁻¹ for the growing season (Sakai et al., 2004), similar to the ET of rice in our site (Table 3). In that region, the mean ET of pasture during the wet season was 2.2 \pm 0.9 mm day⁻¹ and 1.9 \pm 0.6 mm day⁻¹ of ET in the dry season (Sakai et al., 2004), similar to soybeans during the wet and dry month at our site (Table 3).

Energy partitioning

The 10-day average ratios of LE/Rn and H/Rn had significant differences in pattern and magnitude over the three ecosystems (Fig. 6). The ratio of LE/Rn for marshland ranged from 0.3 to 0.6 and H/Rn values varied from 0.2 to 0.5. It is obvious that latent heat flux was the main consumer of Rn for marshland during the peak growing season, and sensible heat flux was the main consumer of Rn in the beginning and end of growing season. These findings are similar to patterns in other wetlands (Admiral et al., 2006; Burba et al., 1999a; Kurbatova et al., 2002; Lafleur et al., 2005). Those values also led to a Bowen ratio ($\beta = H/LE$) (Bowen, 1926) less than 1 at the peak of season and more than 1 at the beginning and end of growing season. Peak β reached around 3 (Fig. 7), probably because more Rn energy was partitioned into H for slow growth rate of plants at the start of growing season. Also, stomatal resistance increases and transpiration decreases as plants began to senesce at the end of the growing season (Vanyarkho, 1996).

The value of LE/Rn was dramatically higher and the H/Rn value was lower for rice than for marshland throughout the growing season, with the value of LE/Rn varying from about 0.5 to 0.8 and H/Rn varying from about 0 to 0.2 (Fig. 6). Consequently, the value of β for rice was significantly lower than one, averaging 0.2 for the whole growing season (Fig. 7).

Table 3 Total precipitation, evapotranspiration (ET), the ratio of ET/P and mean ET rate at marshland, rice and soybeans during growing season (May–October) in 2005, 2006

	ET (mm)		ET/P		ET (mm day ⁻¹)	
	2005	2006	2005	2006	2005	2006
Rain	360	566				
Marshland	361.7 ± 18.8	317.5 ± 17.3	1.01	0.56	2.19 ± 1.05	1.84 ± 0.79
Rice	491.0 ± 19.2	485.3 ± 16.1	1.36	0.86	2.84 ± 1.39	2.76 ± 1.26
Soybean	324.6 ± 12.6	390.1 ± 25.9	0.9	0.69	1.85 ± 0.97	2.23 ± 1.05

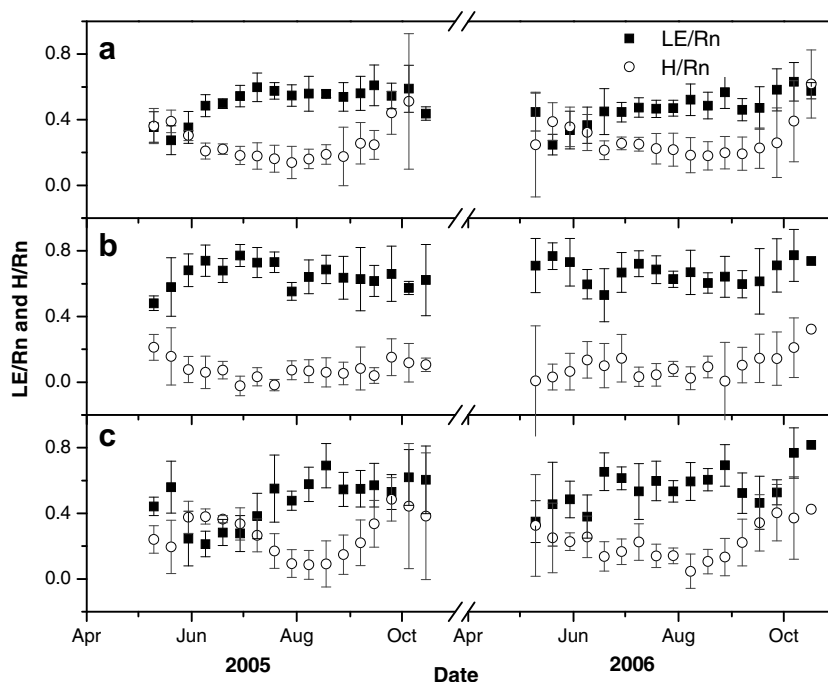


Figure 6 10-Day average energy partition including LE/Rn and H/Rn with error bar (±SD) in (a) marshland, (b) rice and (c) soybeans in 2005 and 2006.

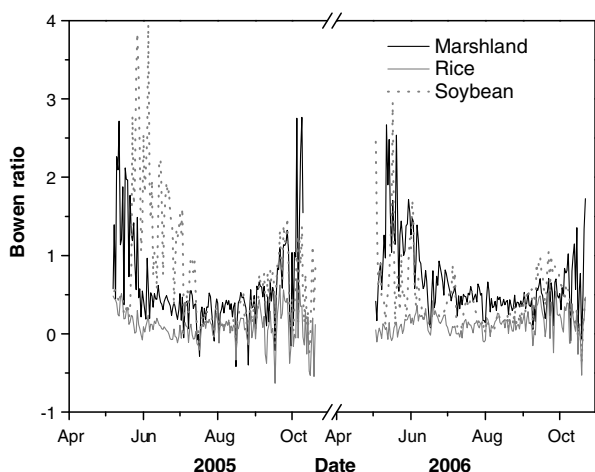


Figure 7 Seasonal variation of daily mean Bowen ratio for marsh, rice and soybeans in 2005 and 2006.

The values of LE/Rn and H/Rn for soybean were close to marshland, whereas a different pattern was observed in June of 2005 and 2006 between marshland and soybean

(Fig. 6). In June 2005, LE/Rn for soybean was lower and H/Rn was higher than marshland, but opposite results occurred in June 2006. The pattern of β for soybean was similar to marshland (Fig. 7). This pattern was also observed in wet grasslands in Japan (peak β about 2 in non-growing season) (Li et al., 2005), in Mer Bleue bog in Canada (high β value about 1.5, and 0.2–0.5 in peak growing season) (Admiral et al., 2006), in Zotino bog (β ranging from 0 to 3, with an average of 0.4 in peak growing season) and in Fyodorovskoy bog (β ranging 0–1.6) (Kurbatova et al., 2002). Because of dry land and conditions for soybeans before July 2005, the value of β reached a maximum value (about 4) in the beginning of the 2005 growing season, and the high value (>1) persisted until early July (Fig. 7).

Dependence of LE and H on environmental conditions

It is well known that ecosystem energy fluxes are principally associated with environmental factors such as solar radiation, soil and air temperatures, soil water availability, and canopy architecture (LAI, species composition, phenology,

etc.) (Baldocchi, 1994; Kelliher et al., 1993; Ruimy et al., 1995). According to Pearson correlation analysis, Rn, PPF, Ta, VPD and LAI have significant relationships with LE over the three ecosystems (Table 4). Furthermore, Rn was generally the most important factor controlling the variation of LE. An exception occurred for soybeans in 2005 when LAI was the primary factor regulating variation of LE. Similarly, Rn or PPF were the most important factors regulating the variation of H over the three ecosystems, and the depen-

dence of H on impact factors was not exactly the same in both years.

The correlation coefficient between LE and Rn for marshland was affected by phenology (Fig. 8a). The slope of the relationship between LE and Rn before May was 0.24 with R^2 at 0.38, which was less than the slope of 0.58 with R^2 at 0.92 after May. This dependence was also confirmed in other ecosystems (Admiral et al., 2006; Kurbatova et al., 2002). The slope of LE and Rn ranged from 0.53 to 0.60 dur-

Table 4 Pearson correlation for dependence of LE and H on environments for different land covers

Variable	Environment parameter	Pearson correlation coefficient (r)					
		Marshland		Rice		Soybean	
		2005	2006	2005	2006	2005	2006
LE	Rn	0.802**	0.741**	0.863**	0.878**	0.467**	0.596**
	PPFD	0.677**	0.616**	0.774**	0.734**	0.464**	0.533**
	Ta	0.787**	0.649**	0.649**	0.504**	0.374**	0.552**
	VPD	0.667**	0.292**	0.784**	0.719**	-0.055	0.161
	LAI	0.381**	0.711**	/	-0.148	0.566**	0.28*
H	Rn	0.522**	0.677**	0.338**	0.268**	0.657**	0.536**
	PPFD	0.649**	0.627**	0.304**	0.395**	0.689**	0.560**
	Ta	-0.246*	0.174*	-0.046	-0.018	0.314**	0.108
	VPD	0.125	0.548**	-0.195*	-0.13	0.737**	0.514**
	LAI	-0.250**	-0.18	/	0.057	-0.461**	-0.513**

Owing to be lack of LAI data for rice in 2005, the correlation coefficient between energy fluxes and LAI was not calculated.

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

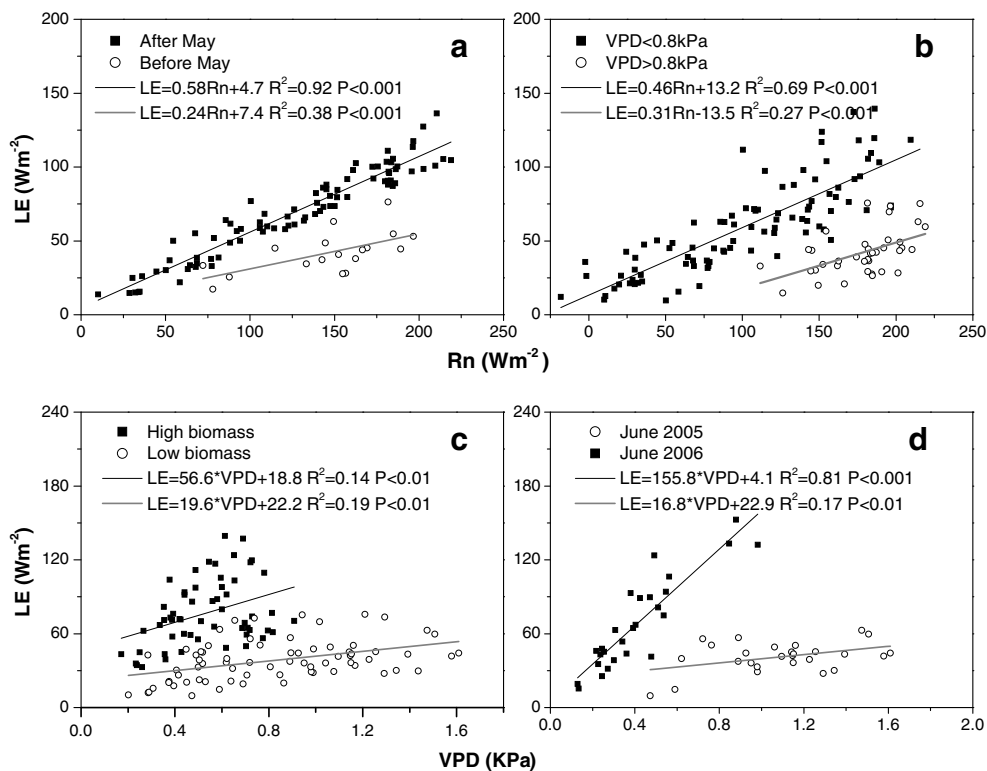


Figure 8 The response of LE on Rn and VPD (a) for marshland in 2005, (b) and (c) for soybean in 2005 and (d) for soybean in June 2005 and 2006.

ing snow-free periods, from 1998 to 2000 over the central Siberian bog. In the European Russia bog, the slope ranged from 0.45 to 0.48 during the same periods (Kurbatova et al., 2002).

Based on Pearson correlation analysis, LE for soybean was not significantly correlated with VPD in either year (Table 4), but there were vastly different responses of LE to Rn in different VPD intervals (Fig. 8b). Likewise, when biomass was divided into >130 g m⁻² and <130 g m⁻² intervals, there was a good relationship between LE and VPD in each interval (Fig. 8c). Due to the variations of water condition in underlying surfaces, LE was responsive to VPD differently in June 2005 and June 2006 (Fig. 8d). The slope (155.8) of the

regression function in wet conditions was almost ten times higher than the slope (16.8) in dry conditions.

Beyond the environmental and biological factors mentioned above, the water depth also played an important role in LE and H for the marshland (Fig. 9). To reduce weather effects, 10-day average LE and H values were calculated excluding cloudy and rainy days. There were weak negative relationships between the depth of water and LE and H.

The effects of all environmental factors were combined together on energy fluxes. According to multiple regression analysis during the measurement periods for two years (Table 5), the integrative factors of Rn, LAI, Ta and VPD can explain about 80% of LE variation and over 50% of the variation for the marshland and rice. They were also the key factors for soybeans, whereas they only explain 30–50% of LE and 60% of H. LE for marshland and rice was positively related to VPD, according to multiple regression models (Table 5). Generally, LE increases with increasing VPD when soil moisture is non-limiting (Jarvis and McNaughton, 1986). Although VPD as a single factor has no significant relationship with LE for soybean (Table 5), VPD was entered into multiple regression functions as an important factor in response to LE and H. Regression models indicated that VPD had a negative effect on LE and a positive effect on H for soybean (Table 5). This finding was contrary to other ecosystems and indicated that water conditions restricted the response of energy fluxes to high VPD. Some documents (Admiral et al., 2006; Kurbatova et al., 2002) suggested that a change in source partitioning for LE led to a change in LE-VPD dynamics.

Conclusion

Land use change from marshland to croplands in Sanjiang Plain had a great influence on water and energy fluxes, energy partitioning and the response of energy fluxes to environmental factors, due to changes in land cover conditions and vegetation categories. The conversion from marshland to rice caused an increase in latent heat flux (LE) and a decrease in sensible heat flux (H) for the growing season, under dry and wet conditions. The monthly ET for rice was the

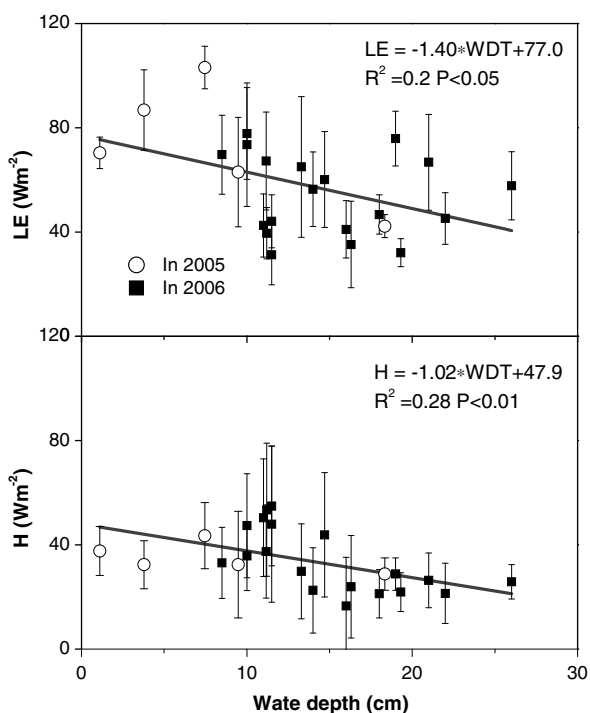


Figure 9 The relationship between 10-day average LE, H and water depth (WDT) at marshland in 2005 and 2006.

Table 5 Multiple regression models for quantifying the dependence of LE and H on environments for different land covers, with stepwise method of SPSS software

	Year	Models	
Marshland	2005	LE = -19.01 + 0.23Rn + 1.38Ta + 30.05VPD + 7.25LAI	(R ² = 0.83, n = 104, p < 0.001)
		H = 40.03 + 0.36Rn - 2.61Ta - 9.87VPD	(R ² = 0.73, n = 104, p < 0.001)
	2006	LE = 16.62 + 0.21Rn + 9.79LAI	(R ² = 0.74, n = 100, p < 0.001)
		H = 12.37 + 0.38Rn - 7.85LAI - 1.25Ta	(R ² = 0.75, n = 100, p < 0.001)
Rice	2005	LE = 2.51 + 0.38Rn + 56.11VPD	(R ² = 0.83, n = 131, p < 0.001)
		H = 12.94 + 0.24Rn - 33.9VPD - 0.91Ta	(R ² = 0.51, n = 131, p < 0.001)
	2006	LE = 1.09 + 0.45Rn + 44.85VPD	(R ² = 0.83, n = 96, p < 0.001)
		H = 23.97 + 0.17Rn - 1.41Ta - 13.75VPD	(R ² = 0.48, n = 96, p < 0.001)
Soybean	2005	LE = 39.62 + 5.44LAI + 0.29Rn - 39.63VPD	(R ² = 0.34, n = 89, p < 0.001)
		H = 24.51 + 30.75VPD - 2.04Ta + 0.30Rn - 5.14LAI	(R ² = 0.73, n = 89, p < 0.001)
	2006	LE = 7.73 + 0.45Rn + 4.13LAI	(R ² = 0.51, n = 58, p < 0.001)
		H = 31.84 - 2.63LAI + 0.20Rn - 2.14Ta + 23.09VPD	(R ² = 0.64, n = 58, p < 0.001)

The order of variable entered for models was priority to high correlation coefficient. There was no LAI data entered in regression analysis between energy fluxes and impact factors for rice in 2005 owing to be lack of LAI data.

highest among the three ecosystems, because of water cover and large above ground biomass. More Rn partitioned to LE resulted in a low Bowen ratio with an average of 0.2 for the whole growing season. However, the effects of conversion from marshland to soybean on water and energy fluxes were strongly dependent on environmental conditions. The LE value for soybeans was lower than that for marshland in the dry conditions of 2005, but was higher than that for marshland in 2006's wet conditions. Among the three ecosystems, the maximum value of β occurred in soybean, and a high value (>1) persisted for a long period under dry conditions. Based on multiple regression analysis, the integrative factors of Rn, LAI, Ta and VPD can explain more variations of LE and H for marshland and rice than for soybean. On the other hand, VPD was a more important factor controlling LE and H for soybean, especially under dry conditions.

Land use changes that cause alterations in water and energy fluxes may affect water balance and energy distribution on a regional scale. However, there were many kinds of marsh categories in the Sanjiang Plain. We do not know how different kinds of marsh affect water and energy fluxes and information about age and areas of agriculture conversion was not clear. Therefore, to completely assess land use change effects on a regional scale, we still need more investigations on regional scale and long-term measurements on water and energy exchanges between ecosystem and atmosphere.

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