Carbon Dioxide Fluxes on a Soybean Field in Argentina: Influence of Crop Growth Stages

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Abstract: CO_2 fluxes were measured in a soybean field in the Province of Buenos Aires, Argentina, with an eddy covariance system consisting of a CO_2/H_2O infrared gas analyzer and a sonic anemometer. The measurements were carried out between 24th December 2008 and 31st March 2009. The measurements continued to be carried out even after the growing season, in order to capture data on the CO_2 fluxes of dying plants and weed plants established after it. Changes in phenology and botanical composition were accompanied with important changes in CO_2 flux values and on the relative importance exercised by three meteorological variables selected to describe the environmental condition: solar radiation, air temperature and vapor pressure deficit (VPD). The maximum CO_2 fluxes were recorded before noon and reached values up to approximately 1.0 mg CO_2 m^{-2} s^{-1}, having a relation with the global radiation and VPD values. This low value was probably associated with the few rain registered during the spring. When senescence took place, respiration processes became more important and the field acted as a source of CO_2. A weak relation was found then with the environmental conditions. Carbon dioxide uptake was reestablished when the soil was covered by weeds but at a much lower rate. The maximum flux value was then around 0.3 mg m^{-2} s^{-1}. Carbon dioxide flux was strongly associated with global radiation, which explained 80% of the variance.

Keywords: Phenological stage, eddy covariance, soybean, multiple regressions, carbon sequestration.

INTRODUCTION

The imbalance between anthropogenic emissions of CO_2 and the sequestration of CO_2 from the atmosphere by ecosystems has led to an increase in the average concentration of this greenhouse gas (GHG) in the atmosphere [1]. Although industrial activities are mainly responsible for the emission of GHGs, changes in agriculture and land-use also have an important influence on GHG emissions and therefore global warming [2]. In this context, terrestrial ecosystems play a key role in the global carbon cycle because of their function as a potential CO_2 sink. An improved understanding of the role played by different ecosystems (forest, grasslands and agroecosystems) at different locations worldwide is essential to obtain global estimations of emissions and the potential of undisturbed ecosystems and sustainable agroecosystems to assimilate CO_2 [3, 4]. Over the past 150 years, the conversion of forests and/or grasslands to agricultural fields has resulted in a 25% of the increase in the accumulation of CO_2 in the atmosphere [5].

There are different methods to investigate the temporal variability of CO_2 assimilation and its dependence on the phenological state of the plants or on meteorological parameters [6]. Several of these methods use satellite-based remote sensing, which allows quantifies the amount of land covered by vegetation and evaluates vegetation-functional aspects [7-9]. The Normalized Difference Vegetation Index (NDVI), a variable parameter derived from red and near-infrared reflectance, has proven to be a good indicator for crops [10] and natural vegetation [11]. Remote sensing provides data on a global scale, but can be related to CO_2 fluxes only indirectly [12, 13] *via* the derivation of vegetation indices. Micrometeorological techniques, however, can be used to measure fluxes of gases, such as CO_2 and water vapor, between the ecosystem and the atmosphere directly [14]. These fluxes can be determined by using the method of covariance of turbulent flow (eddy covariance), calculated from measurements of wind speeds over a coordinated system and the gas concentration in the air. The data obtained with eddy covariance provides information about the diurnal, seasonal and long-term changes of the fluxes; they are particularly suitable to monitor the amount of carbon sequestered and emitted during a growth cycle by ecosystems, such as agricultural land, and to determine the carbon balance [2, 15, 16]. Measurements of different crop systems with different farming practices showed that cropland management has a strong impact on the CO_2 flux dynamics and on net ecosystem production [2, 3].

Argentina is an important country with respect to crop production. Soybean is currently cultivated on approximately 19 million hectares, which represent more than half of the country-wide agricultural land devoted to crop cultivation.

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1874-3315/10 2010 Bentham Open

The frontier of agricultural land has shifted in the recent decades at the expense of grasslands and native forests. Despite the strong impact of this change in land use, the losses of soil organic carbon and the resulting GHG emissions have not yet been comprehensively investigated in Argentina. The lack of precise quantitative data on the emission and sequestration of CO_2 of the main agricultural production systems hampers the implementation of improved farming practices that can either reduce emissions or at least mitigate their increase.

The aim of this paper is to describe the effect of environmental conditions on carbon flux, within and between days in a soybean monoculture during an extreme dry summer. Three different phases according to different phenological soybean stages were selected and compared using multiple regression analysis. The relationship between CO_2 flux and three meteorological variables: air temperature, vapor pressure deficit and global radiation were also evaluated.

MATERIALS AND METHODS

Study Site

Eddy covariance measurements took place on a 360 ha soybean field between December 19th 2008 and March 31st 2009 in Campo de Mayo (34º31'34"S and 58º39'55"W), located approximately 30 km West of the city of Buenos Aires, Argentina. The climate is temperate with a mean air temperature of 24 °C in the summer and 10°C in the winter, with an average annual precipitation of 1147 mm. The soil at this site is classified as a Phaeozem (FAO) and is located 30 m above sea level. The 2008/2009 growing season experienced unusually dry conditions, which resulted in poor crop productivity. During this dry period, the precipitation was 182.9 mm between October and December 2008, and 233.6 mm between January and March 2009. As a means of comparison, the historical mean over 30 years (1961-1990) was 320 mm between October and December and 375 mm between January and March. At the end of January, early senescence began and at mid-February the soybean crop perished. Secondary succession by weed plants then took place. The dominant species of the weed plants were *Portulaca oleracea L* (covering up to 62%), followed by *Anoda cristata L.* Schltdl (covering 20%, estimated through point interception method, data no shown).

The field has been devoted to no-till soybean monoculture cultivation since 1988, and is managed by direct sowing. The sowing usually takes place in October and harvest in March. After harvest the field is abandoned until the next growing season, and secondary succession by weeds occurs after the harvest. In 2008, sowing took place on October 2nd. The distance between crop rows was 0.55 m.

Instrumentation and Analysis

The sensors were installed in the middle of the soybean field approximately 400 m from the tower. The eddy covariance instruments, consisting of an ultrasonic anemometer (USA-1, METEK, Elmshorn, Germany) and a LI-7500 Open Path CO_2/H_2O Infrared Gas Analyzer (Li-Cor Inc., Lincoln, Nebraska, USA), were mounted on a 6 m high metallic scaffold tower at a height of 3.5 m. The data from the anemometer and analyzer were stored with a Panel PC (SYSMEDIA SRL, Rome, Italy) at a frequency of 20 Hz. The raw data were saved on a computer hard disk in the field. The data were downloaded from the disk twice a month for further data processing, which comprised the calculation of covariances and mean values for periods of 30 minutes. Atmospheric convention was used, with negative flux moving downward from the atmosphere to the ecosystem, and positive flux moving upward. In order to calculate the covariances, the time lag between the anemometer and the analyzer was determined by maximizing the covariance between the datasets of both instruments. The planar fit method was used to correct the datasets for a possible slight inclination of the anemometer [17]. The analysis of the anemometer type (Metek USA-1) required a further correction due to lateral wind and the sonic temperature was converted to air temperature [18]. The CO_2 fluxes were calculated by taking into account the fluctuation of air densities, as described by Webb, Pearman and Leuning [19-21]. The flux of CO_2 (mg m^{-2} s^{-1}) is then given by

$$F_{CO2} = \overline{w'\rho_{CO2}'} + \mu \cdot \frac{\overline{w'\rho_v'}}{\overline{\rho_d}} \cdot \overline{\rho_{CO2}} + \left(1 + \mu \cdot \sigma\right) \cdot \frac{\overline{w'T'}}{\overline{T}} \cdot \overline{\rho_{CO2}} \quad (1)$$

where $\overline{w'\rho_{CO2}'}$ is the covariance of vertical wind speed w (m s^{-1}) and density of CO_2, ρ_{CO2} (kg m^{-3}), $\overline{w'\rho_v'}$ is the covariance of vertical wind speed and density of water vapor ρ_v and $\overline{w'\rho_d'}$ is the covariance of vertical wind speed and density of dry air ρ_d; $\overline{\rho_{CO2}}, \overline{\rho_v}$ and $\overline{\rho_d}$ are the mean densities of CO_2, water vapor and dry air (kg m^{-3}), respectively; $\overline{w'T'}$ is the covariance of vertical wind speed and air temperature; $\overline{T}$ is the mean air temperature (K); μ is the ratio of molecular mass of dry air and water (=1.6077) and σ is the ratio of density of water vapor and density of dry air.

The vapor pressure deficit (VPD, in Pa) was calculated using the water vapor density values and air temperatures measured. The stationary conditions of the eddy covariance measurements were tested with the steady state test recommended by Foken and Wichura [22]. The half-hourly data set was partitioned into intervals of 5 minutes and the mean of the covariances of these intervals was compared with the half-hourly covariance. Only fluxes that passed the steady state test were used. The wind came mainly from the North East and South East (35 and 25% of total frequencies). An average fetch distance of 120 m, which captures 80% of the CO_2 flux, was estimated with the footprint model of Hsieh [23]. Taking into account the distance to the edge of the soybean field, we can conclude that fluxes from outside the field do not significantly contribute to the fluxes measured.

Meteorological data such as daily precipitation (TE525 Campbell Scientific), global radiation (CM3·pyranometer, Kipp & Zonen), and mean air temperature (108 Temperature Probe, Campbell Scientific, installed at 1.5 m above ground) were taken every half hour from an automatic station at a distance of 6 km from the field. Field data such as mean crop height and leaf area index (measured with a portable leaf area meter CI-203, CID Inc) were taken during the soybean peak growth. Since cover dynamics was evaluated with LAI measurements, we used values of the normalized difference vegetation index (NDVI) in order to characterize the vegetation growth stages. The NDVI was obtained by reflectance data from band 1 and 2 taken from the MOD09 product. This MODIS product provided composite images every 8 days. The daily diurnal flux values (excluding night data) of the half-hourly data were examined and their relationship with environmental variables (global radiation, vapor pressure deficit and air temperature) tested by simple regression analysis. We then applied a multiple regression analysis to test the improvement of the regression model when all the variables were included in the analysis.

RESULTS

Crop development, as observed during field observations, was clearly identified on the NDVI progress in time. Three contrasting periods were selected to compare available measurement data at different stages of the status of the soybean field: in the first one (period I), the soybean plants were in their growth peak, although the soil was not completely covered; in the second period (period II), plants were in the senescence stage; during the third period (period III), natural succession took place in the abandoned field and weed species were established. The NDVI course in time reflected these changes (Fig. **1**).

Daily Variability

In period I, when the soybean plants reached the peak of growth (in the growing season studied), the highest CO_2 fluxes were around 1.0 mg m^{-2} s^{-1}. At night, CO_2 was released to the atmosphere by respiration, at a rate of 0.2 mg m^{-2} s^{-1} (Fig. **2**). In this period, mean LAI was 1.05, with values between 0.7 and 1.4. Due to the extreme drought in the 2008/2009 summer, the crop did not reach the same maximum height as under normal conditions. The half-hourly diurnal CO_2 flux data showed a significant relationship with each of the environmental variables tested: global radiation, vapor pressure deficit and air temperature. Each variable alone explained little of the CO_2 flux variance (Table **2**). There was a positive relationship with global radiation (the higher the radiation, the higher the CO_2 flux) and a negative relationship with VPD and with air temperature (the higher the VPD or temperature, the lower the CO_2 flux). In the multiple regression analysis, the best model included global radiation and VPD. Due to the correlation between VPD and temperature in this period, the coefficient of the last variable was not significant (P>0.05) in the multiple regression analysis. Both significant variables explained 45% of the total variance (R^2=0.45), i.e. much more than any of the variables separately. Although the relation between CO_2 flux and air temperature is known to be nonlinear, our temperature and global radiation range were limited and the relationship was linear.

In period II, the maximum rate at which CO_2 was assimilated were 0.3 mg m^{-2} s^{-1}. As the crop was dying, respiration (positive flux values) prevailed over photosynthesis and the CO_2 flux values in the course of the day were quite different from those in period I (Fig. **3**). The regression analyses showed no significant relation of the CO_2 flux with global radiation, but a significant relation with VPD and air temperature. However, the variance, which was explained by

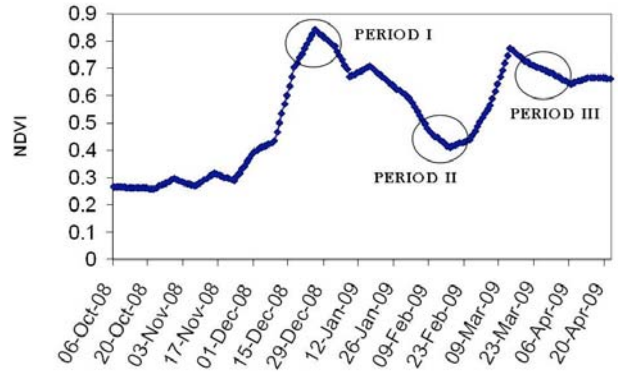

Fig. (1). Normalized Difference Vegetation Index (NDVI) from October 2008 to April 2009 monitored in a soybean monocrop in Buenos Aires province, Argentina. The circles highlight the three periods selected to compare CO_2 fluxes.

Table 1. Dates with Rainy Data (in Millimeters) Recorded by Automatic Station at a Distance of 6 km from the Cultivated Field, from Sowing Day Until the Last Measured Flux Day

Date	rain (mm)	Date	rain (mm)
11-Oct-08	17.5	29-Jan-09	0.5
12-Oct-08	2.5	30-Jan-09	1
14-Oct-08	22	02-Feb-09	11
20-Oct-08	15	05-Feb-09	4
21-Oct-08	14	10-Feb-09	47
25-Oct-08	1.8	20-Feb-09	8.3
19-Nov-08	0.6	21-Feb-09	40
27-Nov-08	45	22-Feb-09	0.5
29-Nov-08	40	28-Feb-09	4.3
1-Dec-08	1	01-Mar-09	25
9-Dec-08	12.5	03-Mar-09	20.5
21-Dec-08	10.5	04-Mar-09	17.5
26-Dec-08	0.5	08-Mar-09	1.5
12-Jan-09	0.7	10-Mar-09	1.5
17-Jan-09	1	11-Mar-09	8
24-Jan-09	0.4	14-Mar-09	0.5
27-Jan-09	10	23-Mar-09	24.8
28-Jan-09	0.6	30-Mar-09	5

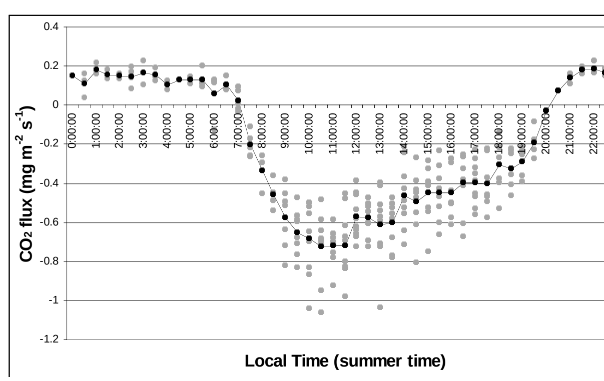

Fig. (2). Carbon dioxide flux over the soybean monocrop on different days in period I (from December 24th 2008 to January 2nd 2009) in Buenos Aires province, Argentina. The line represents half-hourly mean values whereas the dots represent half hourly data.

these two variables, was small: 9.8% for VPD and 18.8% for air temperature respect to total variation (Table **3**). In the multiple regression analysis, the three variables showed sig-

Table 2. Values of the Statistical Parameters Obtained by Simple Linear Regression (Line 1, 2 and 3) of the CO_2 Flux in Period I and Environmental Variables. The Last Row (Multiple Regression Model) Shows the Parameters Obtained from Best Model of Multiple Regression between the CO_2 Flux in Period I and the Three Environmental Variables. Beta is the Slope of the CO_2 Flux in mg m^{-2} s^{-1} Against Global Radiation in W m^{-2}, VPD in Pa and Air Temperature in °C; Intercept is the Value of the y-axis Intercept in mg m^{-2} s^{-1}, R^2 is the Adjusted Determination Coefficient and P is the Significance Level; Significance is Assumed when P is Lower than 0.05

Simple	Variables	Beta	Intercept	R^2	P
1	Global radiation	-2.01E-04	-0.357	0.176	0.000
2	VPD	9.45E-05	-0.704	0.210	0.000
3	Air temperature	1.499E-02	-0.883	0.145	0.000
Multiple	Global radiation	-2.39E-04	0.032	0.455	0.000
	VPD	1.101E-04			

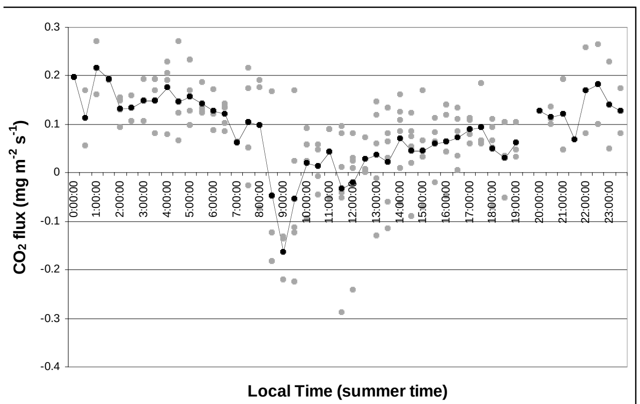

Fig. (3). Carbon dioxide flux over a monocrop soybean field at different days in period II (from 22 to 25 January and 13 to 16 February, 2009) in Buenos Aires province, Argentina The line represents half-hourly mean values whereas the dots represent half hourly data.

nificant coefficients and, together, explained 29% of the variance (Table **3**). It is important to note that in this period the relation between global radiation and air temperature with the CO_2 flux was negative and that the relationship with VPD was positive.

In period III, the CO_2 fluxes were much lower than in period I, although the soil was almost completely covered with weeds by the secondary succession. The maximum value was around 0.3 mg m^{-2} s^{-1} (Fig. **4**). Through respiration, an average of 0.15 mg m^{-2} s^{-1} of CO_2 was released to the atmosphere during night. When the single relationships between each variable and the flux value were tested, we found that only global radiation showed a significant relationship and alone explained 77% of total variance (Table **4**). The multiple regression analysis showed that the three variables together explained 81 % of the variance (Table **4**). The signs of the slope coefficients indicate a positive relationship of CO_2 flux with global radiation and temperature, and a negative relationship with vapor pressure deficit.

DISCUSSION

Our results showed that changes in phenology and botanical composition were accompanied with important changes in CO_2 flux values. In period I, when the crop was growing, the maximum of the CO_2 fluxes were recorded before noon and reached values up to around 1.0 mg CO_2 m^{-2} s^{-1}. These flux values are slightly lower than those found by Prueger *et al.* [24], who report values of up to 1.4 mg CO_2 m^{-2} s^{-1} for a soybean field in the Midwestern USA. This may be due to the intense drought observed during the spring and summer resulting in a depressed growth of the soybean crop. The slow decrease in the afternoon may be related to the lower humidity in the afternoon, leading to a higher vapor pressure deficit, which reduces photosynthesis. The importance of VPD on CO_2 fluxes is also stressed by other authors

Table 3. Values of Statistical Parameters Obtained by the Simple (Line 1, 2 and 3) and Multiple Linear Regression Analysis between the CO_2 Flux and Environmental Variables in Period II. The Statistical Parameters Beta, Intercept R^2 and P are Explained in the Caption of Table 2

Simple	Variables	Beta	Intercept	R^2	P
1	Global radiation	4.686E-05	2.998E-02	0.028	0.057
2	VPD	2.689E-05	-2.38E-02	0.098	0.001
3	Air temperature	9.821E-03	-0.248	0.188	0.000
Multiple	Global radiation	5.289E-05	-0.669	0.289	0.000
	VPD	-8.71E-05			
	Air temperature	3.083E-02			

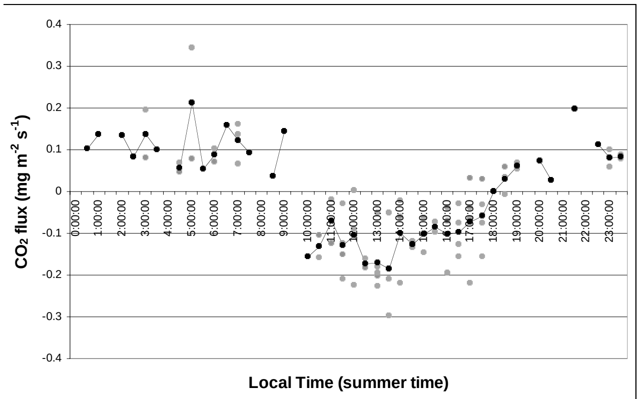

Fig. (4). Carbon dioxide flux over the previous monocrop soybean field, which were succeeded by weeds on different days in period III (from March 23rd to March 31st, 2009) in Buenos Aires province, Argentina. The line represents half-hourly mean values whereas the dots represent half-hourly data.

[e.g. 3, 25], who argue that high VPD leads to higher a stoma resistance and consequently reduced CO_2 assimilation. In period I two of the three environment variables (global radiation and vapor pressure deficit) could explain almost half of the variance of all half hourly data in the period (Table **2**). Air temperature alone showed a slight relationship with the CO_2 flux (R^2=0.145) but its consideration in the multiple regression did not improve significantly the multiple regression due to its correlation with the VPD values. During this period, soybeans were growing under poor environmental conditions, because they were suffering from water stress. The global radiation explains only 18% of the variance.

When the senescence process takes place (period II), respiration processes became more important and had a strong influence on the CO_2 exchange. Only little variance (29%) could then be explained with the meteorological variables. Obviously the photosynthesis is nearly broken down and is replaced by physiological processes related with the dying plants. There is only a small effect of radiation on the CO_2 flux data, probably because photosynthesis is not any more the dominating process. The most influential variable in this period was air temperature, which showed a negative relationship with the CO_2 flux. This negative dependence can be explained by a greater respiration rate, which increases with rising temperatures.

Carbon dioxide uptake is reestablished when the soil is covered by weeds (period III) but at a lower rate, as was shown by Beziat *et al*. [3]. Global radiation showed the highest influence on the CO_2 flux assimilation, explaining 77% of the total variance. Although soil water content measurements are not available, it can be assumed due to the rain which occurred in this period (Table **1**), that the soil water content increased. These improved environmental conditions favored the growing of weed plants, with the result that CO_2 is again assimilated by the biosphere. This explains why in the regression analysis global radiation becomes again an influential variable, which even explained 77% of the total variance. Contrary to the findings in the previous periods, temperature and VPD had a positive relationship with CO_2, however with very low contributions to the total variance.

CONCLUSIONS

The CO_2 fluxes from the soybean monocrop during the extremely hot and dry summer studied showed very different diurnal time course, which depended on the selected periods (peak of soybean growth, death of plants due to the drought, and establishment of weed plants). A maximum of approximately 1.0 mg CO_2 m^{-2} s^{-1} was measured for the CO_2 flux when the soybean plants were growing. As flux data are not available for the whole growing season, the net ecosystem exchange could not be determined for the whole growth cycle. However, the results allowed us to exemplify the changes that took place in the CO_2 balance at different growing stages, both during and after soybean growth. Additionally, a further understanding of the processes that influence the assimilation of CO_2 allow more precise estimations of the net carbon exchange with models, which take into account meteorological variables considering each growth stage particularities.

ACKNOWLEDGEMENTS

Financial support was provided by INTA (project AERN 3632). The Catholic Santa Fe University contributed with a very valuable instrument used on the field, through the assistance of Rudy Grether. The Argentine army seeded the study site and provided field support. We especially thank Colonel Passoli and Lieutenant Colonel Martinez. The doctoral studies of Jorgelina Corin support are supported by CONICET. We appreciate the assistance of Piedad Cristiano, Martín Bellomo, Emiliano Melchiori, Ignacio Oesterheld and Ale-

Table 4. Values of Statistical Parameters Obtained by the Simple (Line 1, 2 and 3) and Multiple Linear Regression Analysis between the CO_2 Flux and Environmental Variables in Period III. The Statistical Parameters Beta, Intercept R^2 and P are Explained in the Caption of Table 2

Simple	Variables	Beta	Intercept	R^2	P
1	Global radiation	-2.64E-04	3.356E-02	0.769	0.000
2	VPD	-7.45E-06	-6.96E-02	0.004	0.681
3	Air temperature	-5.46E-03	-0.248	0.058	0.054
Multiple	Global radiation	-2.37E-04	0.206	0.814	0.000
	VPD	6.069E-05			
	Air temperature	-1.13E-02			

jandro Thompson in the field. The support of CIM, Frankfurt, Germany, for one of the authors (K. Richter) is also gratefully acknowledged. Finally, we thank the three reviewers for their valuable comments and suggestions that greatly improved the paper.

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Received: January 15, 2010 Revised: April 14, 2010 Accepted: April 16, 2010