Analysis of Seasonal Carbon Dioxide Exchange of Winter Wheat Using Eddy Covariance Method in the Northwest Part of Turkey

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Abstract: Increasing concentration of greenhouse gases in the atmosphere has increased the research on the estimation of the greenhouse gas budget components. As it is well known, terrestrial ecosystem is one of the significant components in the global greenhouse gas budget. The aim of this study was to investigate the amount of the CO₂ emissions, which is one of the key greenhouse gases, from winter wheat using the eddy covariance method. The measurements were made over two growing periods on an experiment field at Atatürk Soil Water and Agricultural Meteorology Research Institute (AMRI) in the city of Kırklareli, located in the northwestern part of Turkey. In addition to these, relationships between cumulative CO₂ fluxes and vegetation dynamics such as leaf area index, biomass and normalized difference vegetation index have been investigated under rainfed conditions. Finally, it has been found that the means of accumulated net ecosystem exchange (net carbon sink), gross primary production (carbon fixed by photosynthesis) and respiration (carbon lost by respiration) fluxes during the growing period of winter wheat are -398±43, 1094±48 and 696±91 g Cm⁻², respectively. Strong relations between cumulative CO₂ fluxes and vegetation dynamics have been obtained for winter wheat.

Keywords: CO₂ flux, greenhouse gas exchange, Crop Carbon Balance, Net Ecosystem Exchange.

1. INTRODUCTION

Concentrations of CO₂ and other greenhouse gases are increasing in the atmosphere, which cause global warming and climate change. In order to decrease greenhouse gases concentrations in the atmosphere, many meetings have been held and researchers have been focusing on this topic recently. As it is well known, forests play a very important role in the terrestrial ecosystems through carbon exchange. Hence, most of the studies on the measurement of CO₂ exchanges in the world have been carried out in the forest areas first. Later, similar studies are expanded to the agricultural crops as well because land surfaces absorb and remove CO₂ gas. The Eddy Covariance (EC) method, as one of the micrometeorological methods, has been commonly used for the estimation of greenhouse gas exchanges between the surface and the atmosphere. For example, Falge et al., (2001) determined net ecosystem exchange (NEE) as -183 g C m⁻² (where minus means carbon sink) using this method for the crop surface (wheat) in Oklahoma, USA in 1997. In another study, Anthoni et al., (2004) studied the carbon exchange of winter wheat in Germany using the EC method and estimated cumulative NEE between -185 and -245 g C m⁻² in 2001. In addition, Jun et al., (2006)
determined cumulative NEE for winter wheat grown in the 2002-2003 and 2003-2004 growing seasons in China as -77.6 and -152.2 gC m\(^{-2}\), respectively. They also presented seasonal variations of leaf area index (LAI) and maximal LAI and CO\(_2\) uptake times and their relevance with NEE during wheat growing season. Moureaux et al., (2008) assessed the carbon balance of winter wheat in Belgium for 2004-53 2005 growing season. The variation of green LAI and biomass were examined and also maximal green leaf area index (GLAI) seasons were determined. They found the amount of NEE, Gross Primary Production (GPP) and respiration (R\(_e\)) as -630, 1580 and 950 gC m\(^{-2}\). Aubinet et al., (2009) also investigated carbon exchange of winter wheat at the same location in Lonzée, Belgium using data from 2007 and obtained the amount of NEE, GPP and Re for wheat as -730, 1680 and 950 gC m\(^{-2}\), respectively. Because the daily GPP and Re depend on the type of the crops, GLAI was also measured and associated with GPP values. Dufranne et al., (2011) worked on \(\text{CO}_2\) fluxes of winter wheat in different seasons in Lonzée, Belgium. In the study, GLAI and biomass developments were accompanied by the progressive increases in GPP and Re. At two different locations in the southwest part of France in 2005, \(\text{CO}_2\) fluxes of winter wheat were determined by Bezait et al., (2009) using EC. The cumulative net ecosystem production was estimated as -324±20 gC m\(^2\) and -369±33 gC m\(^2\) at Auradé and Lamasquère, respectively, and correlated with vegetation dynamics such as LAI. Lei and Yang (2010) analyzed seasonal and inter-annual fluctuations of \(\text{CO}_2\) exchange over winter wheat and maize over the North China plain from 2005 to 2009, and it was found that the seasonal totals for NEE for winter wheat varied from -303 to -395 gC m\(^{-2}\) during these four growing seasons. In a similar way, using EC method, seasonal cumulative NEE for winter wheat was estimated by Wang et al., (2013, 2015) in different locations of China between -251 and -359 gC m\(^{2}\), respectively. The results showed that winter-wheat and summer-maize double cropping system acted as carbon source of about 77 gC m\(^{-2}\), annually; carbon sequestration of 90 gC m\(^{2}\) and carbon loss of 167 gC m\(^{2}\), seasonally. Prescher et al., (2010) investigated impacts of land use on the regulation of carbon budgets in eastern Germany and calculated the NEE/GPP ratio for winter wheat as 0.06. Glenn et al., (2010) searched \(\text{CO}_2\) fluxes of spring wheat in Canada. They found that annual cumulative NEE was -240±43 gC m\(^{-2}\) for spring wheat. Besides, Alberti et al., (2010) used the EC method to estimate \(\text{CO}_2\) fluxes for maize and alfalfa crops in the northwestern part of Italy. In addition, Suyker et al., (2005) investigated \(\text{CO}_2\) fluxes of soybean and maize in eastern Nebraska by EC method and estimated cumulative GPP and Re as 1744 and 1154 gC m\(^{-2}\) for maize, 966 gC m\(^{-2}\) and 826 gC m\(^{-2}\) for soybean. Şaylan et al., (2011) studied soybean \(\text{CO}_2\) fluxes during the 2005 growing period in Tottori, Japan and estimated cumulative NEE, GPP and Re as -93, 319 and 226 gC m\(^{-2}\), successively. The relationship between these dynamics and variations in the meteorological factors and LAI were also examined. Schmidt et al., (2012) performed a \(\text{CO}_2\) flux study also for winter wheat in Germany and studied its seasonal and inter-annual variations. They emphasized that the most of the EC research activities were based on short or long term data, depending upon consideration of growing seasons or single years. Vuichard et al., (2016) simulated the NEE, GPP and Re for seven different winter wheat planted areas by using ORCHIDEE-STICS generic model and compared the results with EC flux measurement. The model simulated the seasonal variations of GPP and Re with high accuracy, but the accuracy of simulated NEE was lower compared to those of GPP and Re. Wang et al., (2016) aimed to achieve the best management practices to diminish carbon footprint of winter wheat in the North China plain. Thus, they examined the major resources of greenhouse gas emissions and grain yield to calculate carbon footprint. Their calculations showed that an increase in the nitrogen application and irrigation makes the grain increased, whereas the carbon footprint decreased initially and then increased. Jiang et al., (2014) found a coefficient (from 0.49 to 0.64) between Normalized Difference Vegetation Index (NDVI) and \(\text{CO}_2\) fluxes in Tibetan Plateau in China. Comparing the model results with the measurements, relative errors of 17.5%, 22.9% and 41.7% were determined for NEE, GPP and Re, respectively. Buyyse et al., (2017) used continuous EC flux measurements, biomass samples, meteorological data and crop management practices to obtain NEE, GPP, Re and establish the carbon budget of the cropland over three complete sugar beet (or maize)/winter wheat/potato/winter wheat rotation cycles between the years 2004 and 2016. According to their results, considering whole 12-year period, NEE was negative (-4.34 ± 0.21 kgC m\(^{-2}\)). All these studies summarized above were carried out in different countries and include various agricultural activities and wheat cultivars, and hence, under their characteristic climatic conditions. This makes it difficult for us to compare our results with those in the literature directly. In addition, unfortunately, we cannot make direct comparisons of our results even within our country owing to the lack of research on this subject in the northwestern part of Turkey. Agricultural production plays an essential role
in Turkey’s national economy and food industry. Wheat production in Turkey accounts for the largest percentage of agricultural land usage. 9 million out of a possible 25 million ha are used to grow wheat. Average winter wheat yield in Turkey between 1961 and 2016 was 1901 kg ha\(^{-1}\) with a resulting total production of 16.7 million tons per year (FAO, 2013). These values have been risen up to 2575.7 kg ha\(^{-1}\) and 20.1 tons per year respectively in the last ten-year period (2006-2016). Approximately 3% of Turkey’s total wheat production is in progress for the Thrace Region, which is located in the northwestern part of Turkey. Although winter wheat production has crucial importance, there is a lack of research about the CO\(_2\) exchange of winter wheat in Turkey. Moreover, understanding the effects of the soil, the wheat varieties and agricultural management on CO\(_2\) exchange of winter wheat is also necessary to analyze possible future effects of winter wheat on the climate of Northwest Turkey.

In this regard, it is aimed to (I) measure and estimate the variation of the CO\(_2\) fluxes by means of the NEE, GPP and R\(_e\) of winter wheat over two growing periods by EC method for the first time in the considered region; (II) determine the relationships between cumulated CO\(_2\) fluxes and vegetation dynamics such as biomass, leaf area index (LAI), normalized difference vegetation index (NDVI); and (III) investigate the phenological period which plays major role in carbon exchange.

2. MATERIALS AND METHODS

2.1. Experiment Site
The AMRI is located in the city of Kırklareli/Turkey, on a total area of 34.4 ha. This institute has been responsible for carrying out and leading soil, water and agrometeorological research for almost 35 years. This research was conducted at the experiment field of AMRI for two growing periods (2009-2010 and 2010-2011) of the winter wheat (Triticum Aestivum L.; variety “Gelibolu”) (Fig. 1). The study area (41\(^{\circ}\)41'56"N, 27\(^{\circ}\)12'39" E, 171 m asl) was almost flat with a slope of less than 1% within an approximately 8 ha area. The width and length were 270 and 300 m, respectively for the first growing period (total 15 ha represented by a width of ~ 300 m and a length of ~ 500 m, respectively for the second season). Prevailing wind direction was north.

The fetch length was higher than 185 m for the first and higher than 350 m for the second growing period, respectively. The position of the measurement tower was the same for both growing periods. In the second period, an additional field in the prevailing wind direction was also sown with the same crop. For this reason, the fetch length was extended accordingly in the second period. Distribution of the soil texture for 0-90 cm was 59.0% sand, 25.0% silt and 16.0% clay so the soil was classified as sandy loam. In the 0-90 cm soil layer, average field capacity and permanent wilting point were 0.33 and 0.16 m\(^3\) m\(^{-3}\), respectively.

Winter wheat was sown on 9th October and then harvested on 6th July in the 2009-2010 growing season. Corresponding dates were 25th October 2010 (planting) and 8th July 2011 (harvest) for the successive period. From the climatological point of view, the research site is under the influence of continental climate conditions. According to long-term meteorological data (1959-2017) obtained from Turkish State Meteorological Service (TSMS), annual mean air temperature is 13.3°C and total precipitation
following the gap fraction technique using the LAI-2000 (LI-COR) plant canopy analyzer for three fixed points on the field. As a standard procedure, the measurements were carried out in the frame of one reference sample and four successive measurements throughout each selected row. Using a hand type spectroradiometer (Fieldspec., ASD Inc.) synchronously, the spectral canopy reflectance (between 350 and 1000 nm) of the vegetation was measured on a small tower, which was established ca. 4 m above the surface. Within this context, each measurement process represented the results of five successive measurements for the aforementioned three points by considering a fixed lens angle with regard to the Sun’s present position on the horizon. Collected reflectance data were then finally converted to the corresponding NDVI values. Also crop biomass and height were measured each time on a 1 m² area periodically at three different locations (in an interval of two weeks) during the growing periods.

2.2. Measurements

2.2.1. Agricultural measurements and records

Phenological stages of wheat have been observed and recorded during the above mentioned growing periods (Tab. 1). The second period was started 16 days later than the first one because of the insufficient amount of rainfall for sowing. For this reason, the most of the phenological development stages of winter wheat have been observed later than those in the first period. The experiment field was seeded with winter wheat and fertilized three times with nitrogen fertilizer during each growing period. Additionally, chemical pesticide was applied twice by sprayer for protection against pests and diseases throughout both seasons. Amounts of fertilizers and chemicals were determined by experts on crop protection, soil and agricultural crops. No irrigation was applied during the seasons of interest. For this reason, wheat was grown under rainfed conditions during the growing seasons. Tab. 2 presents information about some agricultural management activities on the crop.

Regular LAI measurements were done biweekly by

is 573.6 mm for the city of Kırklareli. Maximum and minimum air temperature recorded during that period were 42.5 (in July) and -15.8 °C (in January), respectively (TSMS, 2017).

2.2.2. Environmental and flux measurements

In this study, two measurement stations were installed in the experiment field. One of them was the EC system, consisting of an open path infrared gas analyzer (IRGA) (LI-7500, LI-COR); a 3-D sonic anemometer (CSAT3, Campbell Sci.), temperature and relative humidity sensors, (HMP45C, Campbell Sci.) and a

<table>
<thead>
<tr>
<th>Phenological stages</th>
<th>2009-2010 Growing period</th>
<th>2010-2011 Growing period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency</td>
<td>Oct 17th, 2009</td>
<td>Nov 5th, 2010</td>
</tr>
<tr>
<td>Second leaf</td>
<td>Oct 21st, 2009</td>
<td>Nov 10th, 2010</td>
</tr>
<tr>
<td>Third leaf</td>
<td>Oct 26th, 2009</td>
<td>Nov 15th, 2010</td>
</tr>
<tr>
<td>Tillering</td>
<td>Nov 25th, 2009</td>
<td>Dec 7th, 2010</td>
</tr>
<tr>
<td>Stem elongation</td>
<td>Mar 31st, 2010</td>
<td>Mar 29th, 2011</td>
</tr>
<tr>
<td>Earing</td>
<td>Apr 26th, 2010</td>
<td>May 10th, 2011</td>
</tr>
<tr>
<td>Flowering</td>
<td>May 10th, 2010</td>
<td>May 19th, 2011</td>
</tr>
<tr>
<td>Grain filling</td>
<td>May 24th, 2010</td>
<td>Jun 1st, 2011</td>
</tr>
<tr>
<td>Maturity</td>
<td>Jun 4th, 2010</td>
<td>Jun 13th, 2011</td>
</tr>
<tr>
<td>Harvest</td>
<td>Jul 6th, 2010</td>
<td>Jul 5th, 2011</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Applications</th>
<th>Growing period of 2009-2010</th>
<th>Amount</th>
<th>Growing period of 2010-2011</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilization</td>
<td>Oct 9th, 2009</td>
<td>46 kgN ha⁻¹</td>
<td>Oct 25th, 2010</td>
<td>46 kgN ha⁻¹</td>
</tr>
<tr>
<td>Fertilization</td>
<td>Mar 3rd, 2010</td>
<td>69 kgN ha⁻¹</td>
<td>Feb 11th, 2011</td>
<td>69 kgN ha⁻¹</td>
</tr>
<tr>
<td>Fertilization</td>
<td>Apr 8th, 2010</td>
<td>82.5 kgN ha⁻¹</td>
<td>Mar 25th, 2011</td>
<td>49.5 kgN ha⁻¹</td>
</tr>
<tr>
<td>Herbicide treatment</td>
<td>Nov 26th, 2009</td>
<td>0.750 l ha⁻¹</td>
<td>Nov 2nd, 2010</td>
<td>3 l ha⁻¹</td>
</tr>
<tr>
<td>Fungicide treatment</td>
<td>Mar 2nd, 2010</td>
<td>1 l ha⁻¹</td>
<td>Mar 28th, 2011</td>
<td>1 l ha⁻¹</td>
</tr>
<tr>
<td>Fungicide treatment</td>
<td>May 5th, 2010</td>
<td>0.6 kg ha⁻¹</td>
<td>May 16th, 2011</td>
<td>0.6 kg ha⁻¹</td>
</tr>
</tbody>
</table>

Tab. 1 - Phenological development of winter wheat during two growing periods.
Tab. 1 - Sviluppo fenologico del frumento invernale nelle due stagioni.

Tab. 2 - Major agricultural management activities during 2009-2010 and 2010-2011 growing periods.
Tab. 2. Principali interventi agronomici durante le stagioni 2009-2010 e 2010-2011.
data logger (CR1000, Campbell Sci.). The system was established at 2.1 m height above the soil surface to measure the CO$_2$ and H$_2$O fluxes in an interval of 10 Hz. CO$_2$, H$_2$O fluxes were then averaged over 30 min. The distance between the sonic anemometer and IRGA sensor was 20 cm. Data collected in the EC system consist of horizontal and vertical components of the wind, i.e. $u_x$, $u_y$ and $u_z$ (m s$^{-1}$), sonic temperature ($^\circ$C), CO$_2$ mass density (mg m$^{-3}$), H$_2$O mass density (g m$^{-3}$), atmospheric pressure (kPa), vapor pressure (kPa), sensible heat flux (W m$^{-2}$), latent heat flux (W m$^{-2}$), friction velocity (m s$^{-1}$) and wind direction ($^\circ$).

The second station (agrometeorological) was installed at a distance of about 25 m from EC station for the measurements of air temperature (T), relative humidity (RH; at 2 and 3 m heights) (Hygrometer MP100A, Rotronic Inst. Corp); global solar radiation (R$_g$; CMP3, Kipp&Zonen), net radiation (R$_n$; NRLITE, Kipp&Zonen), Photosynthetic Photon Flux Density (PPFD; LI-190SB, LI-COR) sensors (each at 2 m height), rain gauge (P; TE525 Tipping Bucket Rain gauge, Campbell Sci.) at 1 m height, wind speed ($u$) and direction (WD) at 2 m height (NRG #40C, NRG #200F wind direction wane, NRG Systems), soil temperatures at 2, 5, 10, 20 cm depths of soil and soil water content (SWC) sensors (TDR, CS616, Campbell Sci.) at 0-30; 30-60 and 60-90 cm depths. Meteorological data were recorded in 10 and 30 minute intervals by a data logger (CR1000, Campbell Sci.). Meteorological measurements were started approximately two weeks before the planting date of the first season and completed at the end of July, 2011.

### 2.3. Eddy Covariance Method

EC is a commonly used technique to determine the fluxes in atmospheric boundary layer (Baldocchi and Meyers, 1998; Baldocchi, 2003; Burba and Anderson, 2007). General principle of EC method relies on the covariance between concentration of gas which of interest and vertical component of wind speed in eddies. Related equation for fluxes of carbon dioxide ($F_c$) is as follows (Baldocchi et al., 1998; Foken, 2008):

$$ F_c = \overline{w' \rho'_c} $$

(1)

Where, $F_c$ is the CO$_2$ flux; $w'$ represents the deviations of the instantaneous vertical wind speed from the 217 average; $\rho'_c$ is the instantaneous measurement of the carbon dioxide above the average; and overbar indicates time averaging (Baldocchi, 2003; Burba and Anderson, 2007).

For a complete evaluation, NEE flux partitioning between GPP and $R_e$ should be done. In this study, NEE has positive value when CO$_2$ flux is from the surface to the atmosphere and has negative value when the flux occurs in the opposite direction.

EC technique has some disadvantages such as difficulty of the approach, high system cost, correction processes etc. while being a direct method and requiring only few empirical constants are the major advantages (Businger, 1986; Kaimal and Finnigan, 1994). In addition, the method needs some corrections on raw data such as frequency response, WPL (Webb, Pearman, Leuning) and coordinate rotation (tilt). Furthermore, the EC system can produce erroneous data during rainfall and in low turbulence exchange conditions. Hence, resultant gaps in raw data must be filled. Some information is given below for certain corrections in the CO$_2$ flux data.

### 2.4. Data processing and gap filling

The CO$_2$ flux and 3-D wind speed measurements were carried out at 2.1 m high above the soil using an open path infrared gas analyzer. The system measured vertical velocity and the fluctuation of CO$_2$ and H$_2$O concentrations with a 10 Hz frequency. Then, the half-hour fluxes of CO$_2$ (NEE) and H$_2$O were calculated based on the covariance of the vertical velocity and target concentration. Then, calculated NEE was partitioned into GPP and $R_e$ components as in following equation (Reichstein et al., 2005):

$$ GPP = R_e - NEE $$

(2)

All measurements (both at the agrometeorological station and EC flux tower) were started at the beginning of the growing season except the EC system in the first growing season, which started to collect data a bit later on 9th December 2009 due to some technical problems. In the second growing period, a short interval of missing data (only seven days) occurred because of technical reasons again. Abnormal fluxes and sampling errors were extracted from the raw data set; the cross wind coordinate, Webb, Pearman and Leuning (WPL) and rotation corrections were made to obtain the corrected CO$_2$ fluxes, water vapor and energy fluxes (Webb et al., 1980; Leuning and Moncrieff, 1990; Massman, 2000, 2001; Finkelstein and Sims, 2001; Fuehrer and Friehe, 2002). For this purpose, the Edi-Re software was used and quality control analysis (QC) was conducted (EdiRe, 2011). Some data gaps occurred during both growing seasons due to technical problems and unsuitable weather conditions (rain, calm winds during nighttime). Data losses were eliminated using the approaches and software mentioned above. After the corrections, flux data following corresponding rainfall events were
checked and some of them were rejected. Additionally, non-usable data were removed when the friction velocity turbulence was insufficient ($u^*<0.1$ m s$^{-1}$).

Missing values caused by wind direction, stable air conditions and wet days which were filled in accordance with Reichstein et al., (2005) related to quality control for two growing periods varied from 40 to 51% (e.g. steady state tests, $u^*$ criterion, spike 255 detection). Daytime gaps in NEE data were filled according to the following equation (Falge et al., 2001):

$$\text{NEE} = \frac{GPP_{\text{max}} \alpha \text{PPFD}}{\text{PPFD} + GPP_{\text{max}}} + R_e$$

(3)

where $GPP_{\text{max}}$ is the maximum GPP; $\alpha$ is the apparent quantum yield.

In order to evaluate the temperature dependence of nighttime NEE, soil respiration ($R_{e,\text{night}}$) and soil temperature at 5 cm depth were used in the following exponential function. With the purpose of filling the data gap for night time respiration ($R_{e,\text{night}}$), the equation below was used (Lloyd and Taylor, 1994):

$$R_{e,\text{night}} = R_{e,T_{\text{ref}}} \exp \left[ \frac{E_0(T_{\text{ref}} - T_s)}{E_0(T_{\text{ref}} - T_0)} \right]$$

(4)

where $R_{e,\text{night}}$ is the nighttime ecosystem respiration, $T_{\text{ref}}$ is the selected reference temperature (283.15 K) $R_{e,T_{\text{ref}}}$ is the simulated $R_e$ at that reference soil temperature (in K), $T_s$ is soil temperature (in K), $E_0$ and $T_0$ are constants which are 308.56 K and 227.13 K respectively (Falge et al., 2001; Lloyd and Taylor, 1994).

Data gaps in other meteorological variables were filled accordingly with actual data in the second agrometeorological station at the study area, which was established around 400 m away from the experiment field.

Using the Edi-Re software, 10 Hz interval data were analyzed, 30 min. averaged flux data were calculated and finally the data gaps were filled using approaches mentioned. The results based on this data were presented below.

3. RESULTS

3.1. Development of crop

Yields of winter wheat measured for the first and second growing periods were 5090 and 5020 kg ha$^{-1}$, respectively. Biomasses (above ground) at the end of season were 21334 kg ha$^{-1}$ for the first and 24295 kg ha$^{-1}$ for the second growing periods. Furthermore, the maximum LAI in the first period was 3.7, while in the second period it was measured as 4.2. Maximum plant height reached up to 91 cm at the growing period of 2009-2010 whereas it was slightly higher with a height of 93 cm at the end of the second growing period. Fig. 2 shows time series of above ground biomass, plant height and LAI for both seasons.

3.2. Meteorological conditions during growing periods

During the measuring period, winter wheat was grown under rainfed conditions and the total amount of precipitation was 560.7 mm in the first and 339.6 mm in the second growing period. There was a clear difference between the total precipitation amounts of the two seasons. Maximum daily total precipitation was recorded as 33.9 mm on 20th December 2009 during the wetter first season. Fig. 3 shows variations of air temperature, relative humidity, precipitation, wind speed, soil water content (SWC at 0-30 cm depth) and soil temperature ($T_s$ at 5 cm depth) for both periods. Comparison of average temperatures for growing seasons indicates that the first growing period was slightly warmer (1 °C) than the second one. Similarly, average minimum air temperature was higher during the first growing period; represented by -10.8 °C.

Tab. 3 indicates some statistics of meteorological measurements. There, the daily average global solar radiation ($R_g$) in the first growing period was lower (148.5 W m$^{-2}$) than the second growing period (156.6 W m$^{-2}$). Similarly, daily average net radiation ($R_n$) was recorded as 61.7 W m$^{-2}$ during the first season and 65.7 W m$^{-2}$ for the second period. The daytime average net
There was a small difference (0.7%) between the daily average relative humidity values measured at 2 m height above the soil surface for both growing periods. Daily average Photosynthetic Photon Flux Density (PPFD) during the 2009-2010 growing period of winter wheat was 279.2 µmol m⁻²s⁻¹, whereas it reached 284.2 µmol m⁻²s⁻¹ during 2010-2011. Maximum PPFD values were recorded as 692.3 µmol m⁻²s⁻¹ on 12th June 2010 and 688.4 µmol m⁻²s⁻¹ on 21st June 2011 while minimum PPFD values were recorded as 22.8 µmol m⁻²s⁻¹ on 17th December 2009 and 28.7 µmol m⁻²s⁻¹ on 24th January 2011. Fig. 4 shows the variations of Rₑ, Rₑ, and PPFD during the development periods. Additionally, energy balance closure was the same (r²=0.90) in both growing seasons.

Average soil temperature was about 12 °C with a minimum value of -2.4 °C at 2 cm depth. Daily mean volumetric soil water contents at 0-30, 30-60 and 60-90 cm depths were 0.25, 0.27 and 0.31 m³ m⁻³ during the first growing period, respectively. It varied between 0.18 and 0.40 m³ m⁻³ during that time. During the second growing season, this variation was between 0.12 and 0.39 m³ m⁻³. Daily mean soil water content (0-90 cm) was higher in the first season (0.28 m³ m⁻³) than the mean SWC (0.25 m³ m⁻³) of the second period. Minimum SWC values were measured at the beginning of the flowering period in both growing seasons.

### 3.3. Seasonal partitioning of CO₂ flux of winter wheat

Time series of GPP, Rₑ, and NEE during both seasons were obtained on a daily basis (Fig. 5). As seen from the figure, photosynthetic activity (GPP) increased between the second half of March and first week of

<table>
<thead>
<tr>
<th>Meteorological variables</th>
<th>Growing period of 2009-2010</th>
<th>Growing period of 2010-2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature at 2 m (°C)</td>
<td>Daily Ave.</td>
<td>Max</td>
</tr>
<tr>
<td>Maximum air temperature at 2 m (°C)</td>
<td>11.0</td>
<td>27.2</td>
</tr>
<tr>
<td>Minimum air temperature at 2 m (°C)</td>
<td>16.4</td>
<td>37.1</td>
</tr>
<tr>
<td>Global solar radiation (W m⁻²)</td>
<td>6.0</td>
<td>20.2</td>
</tr>
<tr>
<td>Net Radiation (W m⁻²)</td>
<td>148.5</td>
<td>357.0</td>
</tr>
<tr>
<td>Photosynthetic Photon Flux Density (µmol m⁻²s⁻¹)</td>
<td>61.7</td>
<td>207.2</td>
</tr>
<tr>
<td>Soil heat flux (G) (W m⁻²)</td>
<td>279.2</td>
<td>692.3</td>
</tr>
<tr>
<td>Volumetric soil water content (SWC) at 0-30 cm (m³ m⁻³)</td>
<td>-1.35</td>
<td>26.15</td>
</tr>
<tr>
<td>Volumetric soil water content (SWC) at 30-60 cm (m³ m⁻³)</td>
<td>0.25</td>
<td>0.36</td>
</tr>
<tr>
<td>Volumetric soil water content (SWC) at 60-90 cm (m³ m⁻³)</td>
<td>0.27</td>
<td>0.40</td>
</tr>
<tr>
<td>Wind speed at 2 m (m s⁻¹)</td>
<td>0.31</td>
<td>0.42</td>
</tr>
<tr>
<td>Soil temperature at 2 cm (°C) (Tₑₑ)</td>
<td>1.8</td>
<td>9.7</td>
</tr>
<tr>
<td>Soil temperature at 5 cm (°C) (Tₑₑ)</td>
<td>12.0</td>
<td>28.4</td>
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</tbody>
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| Tab. 3 - Statistics of meteorological variables for two growing seasons of winter wheat. Tab. 3 - Statistica delle variabili meteorologiche misurate nei due anni.
May in the first growing period. Later, this activity diminished while CO₂ flux decreased. During the first growing period, daily average GPP, Rₑ and NEE were 4.21, 2.91 and -1.31 gC m⁻², and for the second period they were calculated as 4.09, 2.37 and -1.72 gC m⁻², respectively.

Additionally, maximum GPP values were observed on 25th April 2010 as 13.54 gC m⁻² for the first period and on 11th May 2011 with a value of 16.99 gC m⁻² for the second period; whereas the maximum NEE was estimated as -7.86 gC m⁻² on 26th April 2010 during the first period and as -11.42 gC m⁻² on 11th May 2011 during the second period. Maximum GPP and NEE values were recorded within the phenological phase of earing. In contrast, maximum emission by Rₑ was observed after the maturity phase of winter wheat. Calculated cumulative NEE, GPP and Rₑ were as -354.9, 1142.2 and 787.3 gC m⁻² during the first growing season and -441.3, 1046.8 and 605.5 gC m⁻² for the second season, respectively (Fig. 6). Rates for GPP/Rₑ, NEE/GPP and NEE/Rₑ were 1.45, 0.31 and 0.45 for the first and 1.73, 0.42 and 0.73 for the second periods, respectively. Maximum carbon sink amounts were determined during the beginning of stem elongation and earing stages for both periods. After the maturity stage, NEE gave positive values (from the surface to the atmosphere) for both growing seasons of the crop; as expected.

Maximum carbon was captured during the beginning of stem elongation and earing stages of winter wheat for both growing periods, as shown (Tab. 4-5). Carbon
3.4. CO₂ flux and vegetation dynamics

Focus point of this research is the study of the relationships between CO₂ fluxes and vegetation dynamics such as LAI, biomass and NDVI for two successive growing periods.

3.4.1. Biomass and CO₂ fluxes

Relationships between cumulative CO₂ fluxes such as ∑GPP, ∑Re, ∑NEE and actual biomass of winter wheat were given in Fig. 7 and Fig. 8. As indicated in Fig. 7, there is a high linear relation between cumulative GPP and biomass according to the calculated determination coefficient (r²) of 0.94 for the first growing season. Similarly, high linear relationships between the biomass and ∑Re, and ∑NEE were obtained with r²=0.90 and 0.96, respectively. Fig. 8 shows the linear relations between cumulative CO₂ fluxes and biomass in the second growing season. They revealed strong relationships between ∑GPP, ∑Re, ∑NEE and biomass with coefficients of determination greater than 0.93. They showed that for winter wheat, cumulative CO₂ fluxes are strongly related to biomass.

As seen in Fig. 8, a linear regression is highly adequate to describe the relationship between the NEE and biomass data, which explains 97% of variation in the cumulative NEE of winter wheat.

3.4.2. LAI and CO₂ fluxes

Possible connections between ∑GPP, ∑Re, ∑NEE and LAI have also been investigated in this study (Fig. 9). In order to find a relationship between LAI and...
cumulative CO\textsubscript{2} fluxes, the development period was divided into two groups. First group was defined from planting to LAI\textsubscript{max} (black squares) while the second interval was selected for the senescence period (from LAI\textsubscript{max} to LAI\textsubscript{harvest} (circle points)). The correlation coefficients for LAI-∑GPP relation for these time periods were 0.91 and 0.95; for ∑R\textsubscript{e}, they were 0.96 and 0.82; for ∑NEE they were 0.80 and 0.88, respectively. Thus, more than 80% of the variation in the cumulative CO\textsubscript{2} fluxes may be expressed by the variation of LAI during the first growing period. This suggests that high NEE is the cause of high biomass. Similar significant relations between cumulative CO\textsubscript{2} fluxes and LAI were found for the second growing period of winter wheat as well. As seen in Fig. 10, corresponding coefficients of determination varied between 0.82 and 0.98. These results showed that LAI is strongly related to the cumulative CO\textsubscript{2} fluxes of winter wheat.

As in NEE, high LAI means more biomass, which gives higher GPP and more total biomass for respiration.

3.4.3. NDVI and CO\textsubscript{2} fluxes
NDVI values changed between 0.22 and 0.88 during the first growing period and between 0.15 and 0.95 during the second growing period. Maximum NDVI in the first growing season was determined between the earing and the flowering phases (on 29\textsuperscript{th} April 2010). On the other hand, maximum NDVI for the
second growing period was obtained during the development phases of stem elongation and earing (on 1st May 2011). After the beginning of flowering, NDVI was decreased gradually, and calculated as 0.19 at the harvest stage for the second growing season. As well known, after the emergence the NDVI should increase to its maximum, and the decreasing period is expected till harvest date. Thereby the growing period was divided again into two groups in order to find a relationship between NDVI and cumulative CO₂ fluxes as it was done for LAI. For this purpose, the first group was defined from planting period to NDVI_max. Second time period is determined as the period when the crop is in the senescence stage (from NDVI_max to NDVI_harvest).

Relationships between NDVI and ΣGPP, ΣR_e, ΣNEE for the first growing period are presented in Fig. 11. As given in this figure, the determination coefficients between NDVI and ΣGPP, ΣNEE and ΣR_e were high and varied from 0.78 to 0.98 (except for NEE and NDVI in the senescence period).

Fig. 10 - Relationships between cumulative CO₂ fluxes and LAI of winter wheat in the second growing period.

Fig. 11 - Relationships between CO₂ fluxes and NDVI in the first growing period.

Fig. 12 - Relationship between cumulative CO₂ fluxes and NDVI in the second growing period.

As LAI is related to high biomass, high NDVI means high GPP and NEE. The decrease of NDVI at the end of growing season with much smaller decrease of LAI indicates yellowing of foliage, which decreases first of all GPP and then, to a less degree R_e (why NEE becomes positive).

Fig. 10. Relazioni tra i flussi cumulati di CO₂ e il LAI del frumento invernale nella seconda stagione.

Fig. 11 - Relazioni tra i flussi cumulati di CO₂ e NDVI nella prima stagione.
4. DISCUSSION
In this study, CO₂ fluxes of winter wheat were investigated during two successive growing periods in the northwest part of Turkey for the first time. Currently mostly planted wheat cultivar in the Thrace region of Turkey, was selected. Related EC measurements indicated that calculated NEE, GPP and Rₑ were -354.9, 1142.2 and 787.3 gC m⁻² respectively for the first season. Daily averages of NEE, GPP and Rₑ during growth season were -1.31, 4.21 and 2.91 gC m⁻², successively. Similarly, cumulated NEE, GPP and Rₑ was found as -441.3, 1046.8 and 605.5 gC m⁻², consecutively for the second growth period. In this way, successive daily averages of NEE, GPP and Rₑ during second growing season of winter wheat were obtained as -1.72, 4.09 and 2.37 gC m⁻².

Comparison of net carbon storage value (NEE=-398±43 gC m⁻²) for winter wheat with earlier studies showed that our cumulative NEE values are higher than the estimated NEE by Anthoni et al., (2004) (-185 and -245 gC m⁻²) in Thuringia/Germany, by Falge et al., (2001) (-183 gC m⁻²) in Oklahoma/USA, by Beziat et al., (2009) (-32± 20 gC m⁻²) in Aurade/France, by Wang et al., (2015) 359 gC m⁻² in China and less than the estimations made by Aubinet et al., (2009) (-630 & -730 gC m⁻²) found for Lonzee/Belgium, by Moureaux et al., (2008) (-630 gC m⁻²) also in Belgium and by Schmidt et al., (2012) (-537 & -627 gC m⁻²) in Western Germany. The difference between our average cumulative NEE and the estimated NEE (-369±33 gC m⁻²) by Beziat et al., (2009) for Lamasquere/France is about 7.3%. The differences might be resulted from the crop genetic characteristics and crop management (e.g., fertilizers) and site specifications such as meteorological and soil properties, as Li et al., (2006) mentioned.

Another objective of the research was to assess eventual interactions between the cumulated CO₂ fluxes and vegetation dynamics such as NDVI, LAI and biomass. In order to achieve this, relationships between cumulated NEE, GPP, Rₑ and vegetation dynamics were evaluated during two growing periods. These correlations were investigated by taking successive growing seasons into account. The results have shown that the CO₂ fluxes-vegetation dynamics interactions were very significant for both of the periods. Generally, strong linear and nonlinear relations (0.70≤r²≤0.95) between NEE and vegetation dynamics during the first and the second growing seasons were obtained. This study reveals that the major indicators of vegetation dynamics such as LAI, biomass, NDVI are strongly related to CO₂ fluxes of winter wheat. For this reason, these variables are considered as significant predictors for the carbon exchange above winter wheat.

Same relationships for 2010-2011 growth period were also investigated by separating the growing period, accordingly. Separation was done by considering the variations in NDVI data. Therefore, the first period was chosen from planting to the date when maximum NDVI data were observed and the second period was from NDVI max to harvest date. Strong relationships were obtained between cumulated fluxes (NEE, GPP and Rₑ) and NDVI. Similarly, the correlation coefficient for cumulated GPP and NDVI was 0.74 when NDVI was continuously increasing and 0.98 when it was in continuous decrease. The correlation coefficient between cumulated NEE and NDVI was 0.7 while the increase of NDVI was stable and 0.95 for the opposite situation. Dynamic nonlinear relationships have also been found (r²=0.79 as NDVI increased and 0.96 for the NDVI decreasing period) between cumulated Rₑ and NDVI.

Moreover, it has been achieved that cumulated CO₂ fluxes were highly correlated with LAI for both two growing periods. During the whole first season, the coefficient of determination (r²) between cumulated GPP, NEE, Rₑ and LAI varied between 0.95 and 0.98, in which LAI values were perpetually increasing (0<LAImax<LAI<=LAIharvest). The correlation between CO₂ fluxes and LAI varied from 0.82 to 0.98 while LAI values decreased (LAI<LAImax>LAIharvest). Besides, significant linear correlations have also been found between all cumulated CO₂ fluxes and LAI in the second growing period. Moreover, relations between cumulated CO₂ fluxes and biomass were analyzed for two growing seasons. Within this framework, the correlation between cumulated NEE, GPP, Rₑ and biomass varied from 0.90 to 0.97 for both periods, respectively. High correlation coefficients (about r²=0.97) for ΣNEE and biomass relationship were determined.

In conclusion, a remarkable relationship between CO₂ fluxes and major vegetation dynamics was found. The results of this study pointed that the CO₂ fluxes between winter wheat canopy and atmosphere are under the influence of both meteorological and environmental factors. Clarification of the effects for these factors by conducting related applied studies would enable the researchers to define, explain and model the carbon exchange of winter wheat better. Nevertheless, evaluation of long term EC measurements is necessary for testing the reliability of the relevant model results. Thus, carbon budget of winter wheat can be estimated for wide areas only depending on the long-term measurements. In addition to these, there is an obvious need to measure,
record and pursue fluxes, meteorological factors, vegetation dynamics such as NDVI, LAI and biomass continuously for different crop types. Measuring CO₂ fluxes together with observations and measurements on vegetation dynamics would give a chance to apply the results for larger areas by using available modeling approaches.

Even though agricultural activities and soil were similar in the investigated growing seasons, the CO₂ exchange was influenced by the differences in both total and temporal distributions of precipitation. Technical problems and data loss, which were experienced during the first development period, affected the amount of data in this period especially during the first two months, even though this gap was filled later. For this reason; lower photosynthesis, biomass and LAI were obtained for winter wheat in the first period, despite of the higher total precipitation amount of this first growing season than the second one. Although wheat is one of the widely planted crops in the world, there are however limited studies on the variation of its CO₂ uptake of winter wheat. These results are the first outcomes for the considered cultivar of winter wheat in the Northwest part of Turkey. As wheat is one of the widely planted crops throughout the world, a larger number of quality studies on the variation of its CO₂ fluxes are needed.

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