

Four-year measurement of net ecosystem gas exchange of switchgrass in a Mediterranean climate after long-term arable land use

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Abstract

Switchgrass (*Panicum virgatum* L.) is a perennial lignocellulosic crop that has gained large interest as a feedstock for advanced biofuels. Using an eddy covariance system, we monitored the net ecosystem gas exchange in a 5-ha rainfed switchgrass crop located in the Po River Valley for four consecutive years after land-use change from annual food crops. Switchgrass absorbed 58.2 Mg CO₂ ha⁻¹ year⁻¹ (GPP—gross primary production), of which 24.5 (42%) were fixed by the ecosystem (NEE—net ecosystem exchange). Cumulated NEE was negative (i.e. C sink) even in the establishment year when biomass and canopy photosynthesis are considerably lower compared to the following years. Taking into account the last 3 years only (postestablishment years), mean NEE was -26.9 Mg CO₂ ha⁻¹ year⁻¹. When discounted of the removed switchgrass biomass, ecosystem CO₂ absorption was still high and corresponded to -8.4 Mg CO₂ ha⁻¹ year⁻¹. The estimation of the life cycle global warming effect made switchgrass an even greater sink (-12.4 Mg CO₂ ha⁻¹ year⁻¹), thanks to the credits obtained with fossil fuels displacement. Water use efficiency (WUE), that is the ratio of NEE to the water used by the crop as the flux of transpiration (ET), corresponded to 1.6 mg C g⁻¹ of H₂O, meaning that, on average, 170 m³ of water was needed to fix 1 Mg of CO₂. Again, considering only the postestablishment years, WUE was 1.7 mg C g⁻¹ of H₂O. In the end, about half of annual precipitation was used by the crop every year. We conclude that switchgrass can be a valuable crop to capture significant amount of atmospheric CO₂ while preserving water reserves and estimated that its potential large-scale deployment in the Mediterranean could lead to an annual greenhouse gas emission reduction up to 0.33% for the EU.

KEYWORDS

C fixation, eddy covariance, evapotranspiration, Mediterranean, switchgrass, water use efficiency

1 | INTRODUCTION

Switchgrass (*Panicum virgatum* L.) is a fast-growing perennial grass that has gained importance as potential feedstock for advanced biofuels (Jordan et al., 2007; Lal, 2004; McIsaac, David, & Mitchell, 2010; McLaughlin & Walsh, 1998; Monti, Barbanti, Zatta, & Zegada-Lizarazu, 2012). Previous life cycle assessment studies evidenced a significant potential contribution of ethanol-switchgrass to greenhouse gas (GHG) savings. When compared to annual energy crops such as corn (*Zea mays* L.), fiber sorghum (*Sorghum bicolor* L.) or sunflower (*Helianthus annuus* L.) switchgrass CO₂ eq emissions were estimated 20%–60% lower (Fazio & Monti, 2011), while, if compared to fossil fuels, switchgrass emissions were 115% lower (Adler, Del Grosso, & Parton, 2007), also considering the net carbon exchange of the crop ecosystem with the atmosphere.

Carbon dioxide assimilation/emission is the balance between photosynthesis and respiration of an agricultural ecosystem (soil and plants) and, especially in the case of bioenergy feedstocks, constitutes a fundamental indicator of their sustainability. While aboveground CO₂ fixation of a crop can be easily estimated, the canopy respiration and the total belowground C are difficult to measure, especially at a large field scale. At the same time, evapotranspiration (ET_c) is the second larger term after precipitation in the hydrogeological water balance and the ecosystem water use is a key component of the hydrologic cycle, being intrinsically linked to other biogeochemical cycles through vegetation (Sellers et al., 1997). Extensive introduction of a new crop as switchgrass may produce significant hydrological effects. It has been reported, for example, that perennial grasses can reduce groundwater recharge because of the longer growing seasons and water demand (Schilling, Jha, Zhang, Gassman, & Wolter, 2008) compared to annual crops. Understanding ET_c levels of a perennial crop such as switchgrass can be therefore important to prevent negative consequences. Moreover, the accomplishment of the production of high quantities of biomass to support the development of the bioeconomy should be addressed by minimizing land and water competition with food crops (Dornburg et al., 2010). For example, in the Mediterranean basin biomass crops are expected to be mostly developed on marginal or abandoned land under semiarid conditions. On the whole, water use efficiency (WUE, i.e. the amount of carbon gained per consumed water) is critical in the selection of the most appropriate biomass crop and to assess the impact of the potential large deployment of a crop on local basin hydrology (VanLoocke, Twine, Zeri, & Bernacchi, 2012). Perennial species, such as switchgrass, allocate great amounts of C belowground (Dohleman, Heaton, Arundale, & Long, 2012; Kahle, Beuch, Boelcke,

Leinweber, & Schulten, 2001; Neukirchen, Himken, Lamme, Czypionka-Krause, & Ols, 1999), which should not be neglected when calculating WUE. A high WUE reflects the opportunity for a crop to provide an ecosystem service, the carbon accumulation, compared to a perceived environmental cost of this service, that is the consumed water.

Although switchgrass and, more in general, perennial grasses are recognized to be able to sequester significant amounts of soil C (up to 10.1 Mg ha⁻¹ year⁻¹ in the short term and averaging <1.0 Mg ha⁻¹ year⁻¹ in the long term; Anderson-Teixeira, Davis, Masters, & Delucia, 2009; Frank, Berdahl, Hanson, Liebig, & Johnson, 2004; Liebig, Johnson, Hanson, & Frank, 2005), little information is present in the literature on their carbon storage potential in the Mediterranean area, especially at the ecosystem level. Switchgrass was shown to be able to produce considerable amounts of biomass under a Mediterranean climate in the long term (10.0 and 13.6 Mg ha⁻¹ year⁻¹ in Greece and Italy, respectively; Alexopoulou et al., 2015), increasing also soil-associated organic C (SOC) content by 0.09 g kg⁻¹ year⁻¹ (stock increase was estimated between 0.37 and 1.58 Mg ha⁻¹ year⁻¹) in the long term (Nocentini & Monti, 2017). However, other studies in different regions have also shown C losses after conversion into switchgrass (Garten & Wullschleger, 2000; Qin, Dunn, Kwon, Mueller, & Wander, 2016; Zenone, Gelfand, Chen, Hamilton, & Robertson, 2013), with the difference often due to the land-use change, as the former land use usually influences ecosystem C stocks and subsequently the capacity of a new established crop to increase them (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008; Qin et al., 2016). Switchgrass was reported to lose SOC when replacing grassland (−1.0 Mg ha⁻¹ year⁻¹, on average; Qin et al., 2016) while increasing it when replacing cropland (+1.28 Mg ha⁻¹ year⁻¹, on average; Qin et al., 2016), but, for example, Zenone et al. (2013) also reported a C loss of 1.49 Mg ha⁻¹ year⁻¹ in the first years of switchgrass cultivation following a corn–soybean rotation in Michigan (USA).

In this study, we addressed CO₂ and H₂O fluxes in a 5-ha switchgrass field for four consecutive years and after the land-use change from long-term cultivation of annual food crops (at least, 60 years of arable land use). Fluxes were measured through an eddy covariance tower (Owen et al., 2007) at the ecosystem level. Eddy covariance data were validated and integrated with root, soil and aboveground biomass measurements. Although the ecosystem C balance measured with the eddy covariance represents a substantial component of its life cycle global warming impact, to assess the effect on GHG emissions of establishing switchgrass, other sources, direct and indirect, were taken into account. Following methodologies from previous

life cycle studies (Adler et al., 2007; Fazio & Monti, 2011), emissions produced by agronomic inputs during cultivation were assessed. Nitrous oxide (N₂O) emissions, which can substantially impact agricultural production cycles (Reay et al., 2012), were modeled as well (Parton, Hartman, Ojima, & Schimel, 1998). Although switchgrass biomass can be used for several purposes, CO₂ credits from displacing fossil fuels by converting switchgrass harvested biomass in advanced ethanol were taken under consideration (Gelfand et al., 2011; Lynd et al., 2008; McLaughlin & Walsh, 1998). This study did not consider the indirect land-use change (ILUC) effect of displacing food production to cultivate switchgrass, as its estimation is still highly uncertain (Plevin, O'hare, Jones, Torn, & Gibbs, 2010; Zilberman, 2017). The ILUC effect represents the CO₂ emission deriving from the conversion of more land somewhere else to recover the lost commodities substituted by biofuel (Searchinger et al., 2008).

The ultimate objective of this study was the multiyear farm-scale level determination of ecosystem C and water gas exchange of switchgrass grown with conventional agricultural practices and machinery, to then include the data in an assessment of the life cycle global warming potential and WUE of advanced ethanol production. To the best of our knowledge, there are no studies reporting direct multiyear continuous measurements of the net ecosystem gas exchange of switchgrass in the Mediterranean Europe. Furthermore, this is one of the few studies that assessed the life cycle global warming potential of the land-use change from annual food crops to switchgrass integrating eddy-covariance measurements, as previous studies mainly focused on the land-use change from perennial vegetation systems as set-aside grasslands (Gelfand et al., 2011, 2013). The conversion of marginal cropland to biofuel production might become common in future biomass supply districts to fulfill the demand by the transformation plants.

2 | MATERIALS AND METHODS

2.1 | Site description and management

The experiment was carried out in a 5-ha flat field of the experimental farm of the University of Bologna (44.55 N, 11.41 E, 33 m a.s.l.), located in Cadriano, in the Po River Valley (North Italy). Carbon and water fluxes were monitored on switchgrass (*P. virgatum* L., cv. Alamo) over a 4-year period (May 2012–June 2016). The soil was classified as Udic Ustochreps fine-silty, mixed mesic (USDA classification), with a pH of 7.2, and high exchangeable calcium. Soil organic carbon was 10.1 g/kg (1.6% of organic matter), total N content was 1.2 g/kg, and C/N ratio equal to 8.0. The available P and K were not limiting (57 and 161 mg/kg, respectively). Switchgrass was sown on 23

April 2012, 45 cm row spaced. Wheat (*Triticum durum* Desf.) – sugar beet (*Beta vulgaris* L.) was the conventional crop rotation adopted before switchgrass plantation. Seedbed preparation included plowing in autumn, harrowing and mechanical hoeing in spring. Fertilization was 230 kg/ha of P₂O₅ only in presowing, whereas, starting from the second year, N was applied annually at a rate of 50 kg (N) ha⁻¹ as urea. Weeds control occurred only during the establishment by spraying *Agherud Dicamba* (3,6-dichloro-2-methoxybenzoic acid; 1 L/ha), *Harmony 50sx* (tribenuron metil 50%; 10 g/ha) and *Starane gold* (fluroxypyr-meptyl, florasulam; 1 L/ha). Irrigation was never applied. Switchgrass was mechanically harvested in autumn (October) each year; stems were cut at ~5 cm from the ground. After cutting, biomass was baled and removed from the field. After each mechanical harvest, biomass losses (residue) were measured on ten random areas (6 m² each) across the field. Biomass moisture concentration was determined by collecting and drying (oven-dried at 105°C until constant weight) biomass samples taken from ten bales and from residue biomass.

2.2 | Carbon and water measurements

Carbon and water vapor fluxes monitoring started on 11 May 2012. Given the relatively small size of the field, to ensure the most proper flux representation, a wind footprint analysis was performed continuously during a 8-month period, following the methodology proposed by Schuepp, Leclerc, Macpherson, and Desjardins (1990). Data confirmed that about 90% of the measured fluxes originated from the switchgrass, thus revealing the correct positioning of the tower (Figure 1). A three-dimensional sonic anemometer (Metek, GmbH, Germany) and an open path infrared absorption gas analyzer (IRGA, Li7500; LiCor Inc., USA) for measuring, respectively, carbon and water fluxes, were placed at 3.5 m height (about 2 times the height of switchgrass canopy at full elongation). Eddy measurements were coupled with a net radiometer (Kipp&Zonen CNR1) for detecting the net available energy at the canopy surface, and to calculate energy balance; flux plates (Hukseflux HFP01-10) were installed to compute the soil heat flux. Also, placed at two different soil depths (15 and 30 cm), there were four water probes (ECHO-5 Decagon) and six thermocouples to measure soil moisture and temperature. Wind, H₂O, CO₂ and temperature were sampled at high time resolution (10 Hz) and released as 30 min integral per square meter and per second. All data were stored on a CR1000 (Campbell Sci., USA) data logger, remotely accessible. Data processing followed the guidelines of the standard EUROFLUX methodology (Aubinet et al., 1999). The half-hour mean flux values were computed in the postprocessing by covariance analysis between

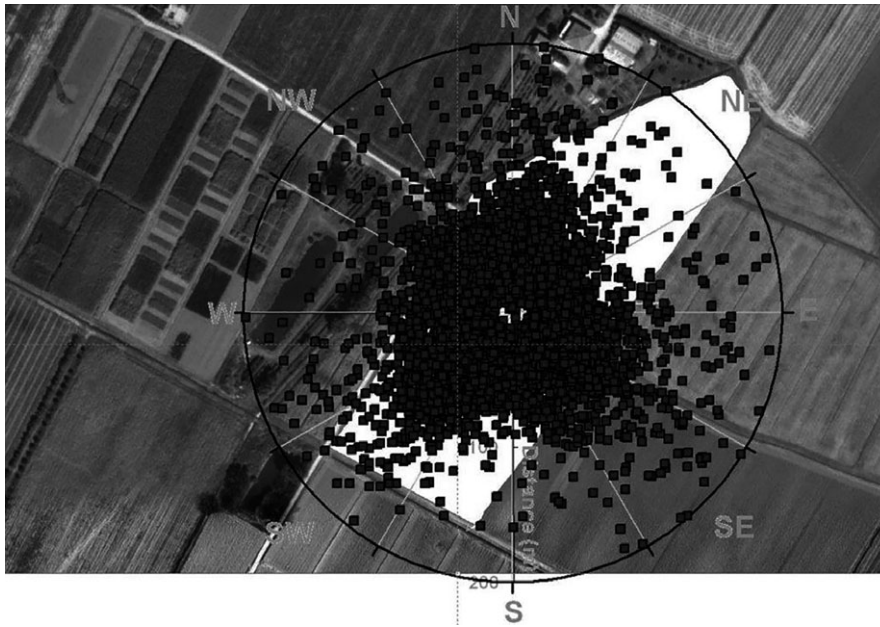


FIGURE 1 Eddy covariance footprint analysis; 90% of the measured flux originated from the switchgrass field (white area)

w and the scalars c , q and T , where w is the vertical component of the wind speed vector, c and q are the concentration of CO_2 and H_2O , and T the air temperature. Postprocessing and quality check were applied to raw data together with specific routines, as running mean to avoid detrending problems, three angle coordinate rotations of the wind vector to remove the effects of instrument tilt or terrain irregularity on the airflow, despiking and stationarity (Derbyshire, 1995).

Gaps due to unfavorable micrometeorological conditions, instrument failure and data quality check that occurred during the entire monitoring time, led to a data coverage of 66.1% of the whole period. Gap filling was then carried out on the remaining 33.9% of data with the use of the online tool “eddy covariance gap-filling and flux partitioning” of the Max Planck Institute methodology.

The gap filling of the eddy covariance and meteorological data are performed with methods similar to Falge et al. (2001), but also considering the covariation of fluxes with meteorological variables and the temporal autocorrelation of the fluxes (Reichstein et al., 2005). In this algorithm, three different conditions are identified:

1. Only the data of direct interest is missing, but the meteorological data are available for radiation (R_g), air temperature (T_{air}), and vapor pressure deficit (VPD).
2. Also T_{air} or VPD are missing, but R_g is available.
3. Also R_g is missing.

Case 1: The missing value is replaced by the average value under similar meteorological conditions, that is with

a look-up table (LUT), within a certain time window. Similar meteorological conditions are present when R_g does not deviate by more than 50 W/m^2 , T_{air} by 2.5°C , and VPD by 5.0 hPa . If no similar meteorological conditions are present within the starting time window of 7 days, the windows size is increased to 14 days.

Case 2: The same LUT approach is taken, but similar meteorological conditions can only be defined via R_g within a time window of 7 days.

Case 3: The missing value is replaced by the average value at the same time of the day (1 hr), that is by the mean diurnal course. In this case the window size starts in the same day, thus a linear interpolation of available data at adjacent hours.

If after these steps the values could not be filled, the procedure is repeated with increased window sizes until the value can be filled.

Night data were inspected to detect invalid values (i.e. negative values of carbon dioxide flux, values of respiration outside of the trend), in order to avoid the underestimation of the nocturnal surface exchanges (Aubinet et al., 1999; Göckede et al., 2008; Twine et al., 2000). Positive CO_2 and H_2O values will indicate gas emissions to the atmosphere. CO_2 fluxes were measured to estimate the photosynthetic uptake or gross primary production (GPP) and ecosystem respiration (R_e). GPP represents the total amount of CO_2 that is uptaken by the ecosystem through autotrophic fixation while R_e represents the CO_2 released by all agroecosystem metabolic activities. The net ecosystem exchange (NEE), that is the amount of carbon which has been stored in the above-, belowground biomass and

SOC, was obtained as difference between GPP and R_e . We estimated switchgrass ETc through water vapor released by the system. It was calculated by dividing latent heat flux by the latent heat of vaporization. Ecosystem WUE was then calculated dividing GPP or NEE by ETc. Daily rainfall, air temperature and solar radiation were also collected by a meteorological station inside the experimental farm.

2.3 | Litter, root and soil samplings

Litter biomass, which formed because of the accumulation, year after year, of the losses from mechanical harvest, was collected in November 2015, at the end of the fourth growing season, on ten 0.25 m² areas, randomly distributed across the field. Subsamples were taken from each sample then oven-dried (at 105°C until constant weight) for moisture content determination.

In June 2012 and November 2015, three soil cores (70 mm ϕ) were collected by a mechanical auger down to 0.45 m soil depth, in ten sampling areas across the field (same areas where litter was sampled). In each sampling area, the three soil cores were collected within the row, next to the row and in the inter-row, in order to take into account spatial differences in belowground C. In total, 60 soil cores were collected (3 soil cores \times 10 sampling areas \times 2 years). Samples were air-dried: then litter residues were manually removed, root biomass was manually separated from the soil, washed, sieved and oven-dried (105°C) for 72 hr, while the remaining soil was ground to 0.5 mm, before analyzing for organic C content and ¹³C isotope abundance; ¹³C abundance allowed to specifically determine switchgrass (C4)-derived SOC as C3 species were cultivated in the previous 2 years (wheat–sugar beet). After being oven-dried at 60°C, subsamples of aboveground and belowground biomass were analyzed to measure their C content. Soil subsamples (~15 mg) were pretreated with HCl to eliminate inorganic C and encapsulated thereafter. SOC was determined by an elemental analyzer (Flash 2000 CHNS/O Analyzer, Thermo Scientific, USA), while carbon isotope composition was determined through CF-IRMS continuous flow-isotope ratio mass spectrometry (Delta V advantage, Thermo Scientific, USA). Plant material subsamples (~0.5 mg) were analyzed with the same instrumentation. To calculate C stocks variations starting from SOC concentrations in the soil, soil bulk density was measured at two depths (15 and 30 cm), using metal cylinders (volume = 98 cm³) and collecting a total of 12 samples (3 samples \times 2 depths \times 2 years).

2.4 | Biogenic N₂O emissions and CO₂ emissions from inputs and fossil offset

To obtain a full estimation of the impact of the farm-scale switchgrass field on GHG emission, biogenic N₂O

emission and the CO₂ released or taken up indirectly were also taken into account.

As our eddy covariance system was not equipped to measure N₂O fluxes, we estimated N₂O emission with the DAYCENT model (Parton et al., 1998). DAYCENT was calibrated and validated for Cadriano's switchgrass field, also using the data measured by the eddy covariance tower, in a recent work where a detailed description of the modeling can be found (Nocentini, Di Virgilio, & Monti, 2015).

Equivalent CO₂ emissions from the agronomic inputs applied to the switchgrass field were estimated. Taking into account all field operations carried out and materials (i.e. seeds, fertilizers, herbicides) used (Table 1), and after interviewing the workers of the experimental farm about the machines used and the time and diesel spent per hectare for each operation, we were able to perform an analysis with the life cycle software SimaPro 8.0 (PRé Consultants, Amersfoort, The Netherlands). Processes already present in the Ecoinvent 3.0 database were modified to better reflect the field operations observed in terms of diesel use and machines consumption. At last, equivalent CO₂ emissions caused by each process were calculated employing the IPCC 2013 GWP methodology (IPCC, 2014). Emissions generated during switchgrass establishment were annualized, assuming that the economic life of the stand was 10 years (Qin, Mohan, El-Halwagi, Cornforth, & McCarl, 2006).

Also, the CO₂ indirect uptake (credit) deriving from displacing fossil fuels was estimated, as the lignocellulosic harvested biomass could be used to produce

TABLE 1 List and count of field operations and agronomic inputs for switchgrass cultivated at the experimental farm (North Italy) in the years from 2012 to 2016. The following information was used to estimate life cycle emissions. Emissions generated during switchgrass establishment were annualized over the 10-year economic life of the crop

Inputs	Units	Value
Plowing depth	m	0.4 ^a
Disk harrowing	n	1 ^a
Tine harrowing	n	1 ^a
Seeds	kg/ha	9 ^a
N fertilizer	kg ha ⁻¹ year ⁻¹	50 ^b
P fertilizer	kg/ha	230 ^a
Hoeing	n	1 ^a
Herbicides	n	2 ^a
Pesticides	n	—
Harvesting	Type	Baling

Note. ^aEstablishment. ^bFrom 2nd year.

advanced ethanol. Lynd et al. (2008) reported that 282 L of EtOH can be produced from 1 ton of dry biomass. Thus, considering an energy density for advanced (ligno-cellulosic) ethanol of 21.1 MJ/L and C savings equal to 90 g CO₂ MJ⁻¹ of energy produced (Gelfand et al., 2011), offset credits could be calculated.

2.5 | Flux terminology

The ecosystem CO₂ autotrophic fixation per unit of time and area is GPP (negative sign). The ecosystem CO₂ respiration per unit of time and area is R_e (positive sign). The difference between these two fluxes results in the net CO₂ exchange of the ecosystem with the atmosphere (NEE):

$$NEE = GPP + R_e \quad (1)$$

The cumulated NEE is then subtracted of the C removed through biomass harvest to obtain the net ecosystem C balance (NECB), which represents, for the switchgrass ecosystem, the sum of litter, root and change in soil-associated C:

$$NECB = NEE_{\text{cumulated}} + C_{\text{harvested}} \quad (2)$$

The water vapor released by the ecosystem represents the ETc. The ecosystem WUE was calculated as the amount of C fixed per unit of water released:

$$WUE = \frac{NEE}{ETc} \quad (3)$$

The life cycle GHG balance was estimated by accounting for all direct and indirect emissions: NECB, biogenic N₂O emission, cultivation emissions (from agronomic inputs), and fossil fuel offset credits obtained by producing renewable energy with the switchgrass harvested biomass:

$$GHG = NECB + N_2O + \text{cultivation} + \text{offset credit} \quad (4)$$

3 | RESULTS

3.1 | Environmental conditions

The experimental site falls within the Mediterranean North agroclimatic zone as described by Metzger, Bunce, Jongman, Mucher, and Watkins (2005). Local long-term measured annual precipitation (30 years) corresponded to 708 mm, while 30-year maximum, minimum and mean T_{air} were 18.2, 8.2 and 13.2°C, respectively. Weather and soil temperature and moisture data for the period of the experiment are reported in Table 2, while Figure 2 shows the time course of temperatures and rainfalls. Mean T_{air} during investigation was slightly higher than the long-term value, ranging from 13.8 to 14.8°C, with 2013 being colder than other years. T_{air} varied the most during the growing seasons (April–October) through the years, from 19.4 to 22.1°C (Table 2). Soil temperature (T_{soil}) significantly decreased from first to second year, probably due to the cooling effect of the tall and dense established switchgrass. Annual precipitation was similar in 2013 and 2014, lower in 2015 and significantly lower in 2012; on average, it was close to the long-term value for the site (721 mm). On the other hand, distribution of monthly precipitation was also different among years (Figure 2): for example, although showing similar values of annual precipitation, the years 2013 and 2014 had the driest and the rainiest growing seasons, respectively (Table 2).

Soil water content greatly varied among years and within the same growing season. Observing cumulative ETc and precipitation, the site apparently experienced a negative water deficit (i.e. the difference between

TABLE 2 Yearly and growing season mean air and soil temperature, mean soil water content (SWC; upper 30 cm), cumulative precipitation and evapotranspiration (ETc), and water deficit (WD) at the experimental field

Year	Σ rain (mm)	Mean temp (°C)		Mean SWC (mm)	Σ ETc (mm)	WD (mm)
		Air	Soil			
2012	575.2	14.4	16.1 ^a	86.2 ^a	319.1 ^a	256.1
2013	802.3	13.8	13.2	97.6	453.2	349.1
2014	829.0	14.8	14.4	57.6	489.4	339.6
2015	678.8	14.5	16.2	48.7	340.2	338.6
April–October 2012	420.8	22.1	22.5 ^a	84.2 ^a	296.9 ^a	123.9
April–October 2013	322.6	19.8	21.8	96.3	380.2	−57.6
April–October 2014	478.4	19.4	21.8	44.1	413.4	65.0
April–October 2015	382.0	20.2	21.8	46.5	277.0	105.0

Note. ^aFor the year 2012, cumulated and mean values were calculated starting from May.

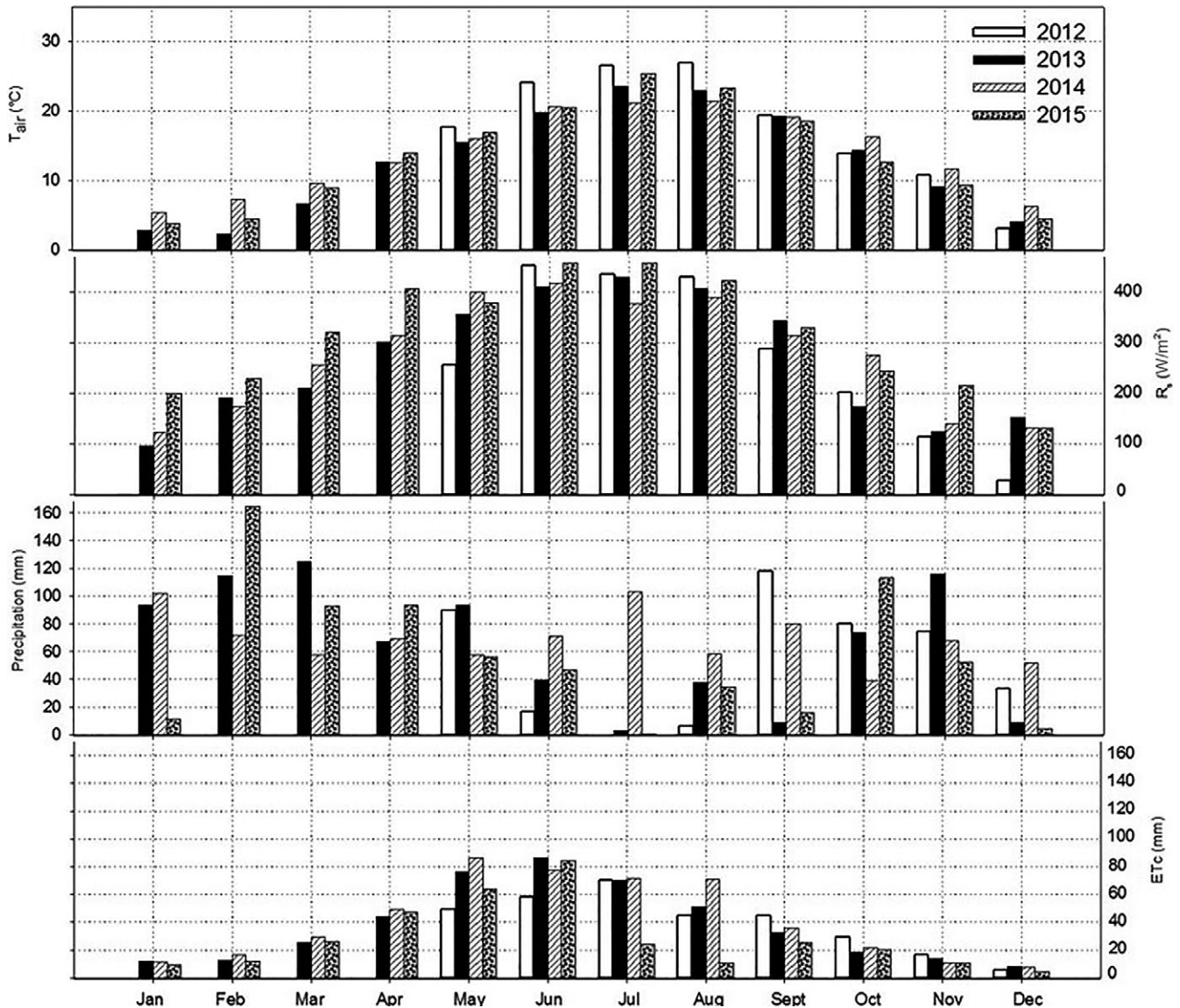


FIGURE 2 Monthly average air temperature and shortwave incoming radiation (R_s), and cumulated monthly precipitation and evapotranspiration (ETc) during the 4 years of the experiment

precipitation and ETc) only during the second growing season (Table 2); however, during summer, in July and August, water deficit assumed sometimes negative values also in other years.

3.2 | Energy balance closure

The ecosystem energy balance closure (EBC) is an important test to evaluate the reliability of the eddy covariance data, as an unbalance leads to underestimate CO_2 fluxes (Mauder et al., 2007; Moncrieff, Malhi, & Leuning, 1996). EBC requires that the sum of the estimated latent (LE) and sensible (H) heat flux are equivalent to all other energy sinks and sources, as expressed in the following equation:

$$LE + H = R_n - G - S - Q \quad (5)$$

where R_n is the net radiation, G is the heat flux into the soil, S is the rate of change of heat storage (air and biomass) between the soil surface and the level of the eddy covariance instrumentation, and Q is the sum of all additional energy sources and sinks. In a typical manner, Q is neglected as a small term.

Only high-quality fluxes of H and LE were used and EBC was calculated only when all four measurements (H , LE, R_n , and G) were available. The fraction of half-hourly values of turbulent fluxes ($H + LE$) and available energy ($R_n - G$) were 0.84, 0.70, 0.77 and 0.71 from 2012 to 2015, respectively (Figure 3), indicating that, despite a likely underestimation of G , the eddy covariance

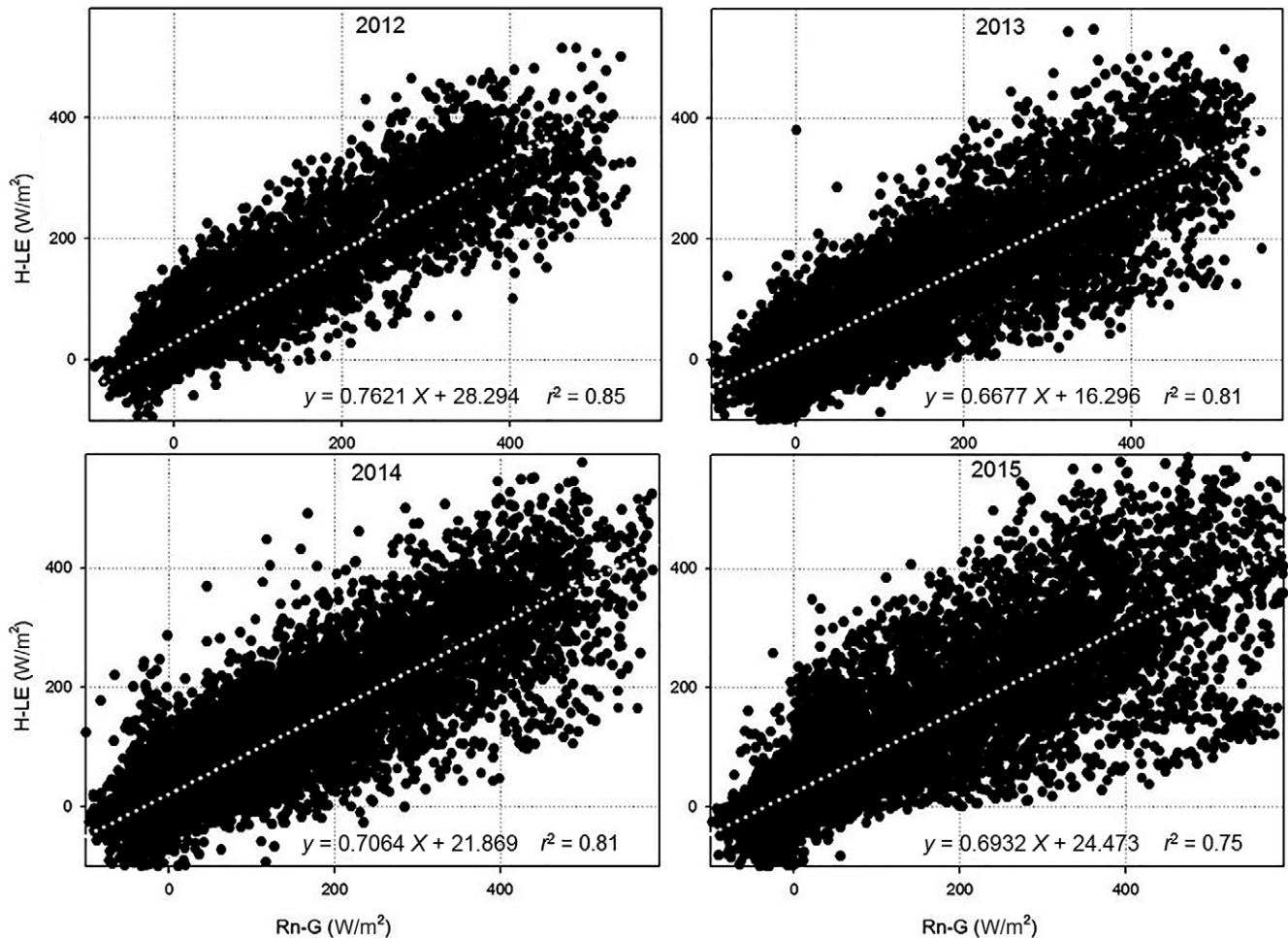


FIGURE 3 Annual superficial energy balance in the years 2012, 2013, 2014 and 2015

measurements can be considered as reliable, also compared with other studies (Mauder et al., 2007; Twine et al., 2000). The heat contained in the biomass can be included in the balance (Wilson et al., 2002), while punctual measurements of soil temperatures and moisture should be repeated in several locations over the field to obtain a more representative value of G (Meyers, 2004).

3.3 | Fluxes of CO₂

The GPP increased significantly from the first to the second year and, to a lesser extent, from the second to the third year, while it slightly decreased in the fourth year (Figure 4; Table 3). Within the growing season, GPP ranged from -37.8 (establishment year) to -58.8 (third year) Mg CO₂ ha⁻¹. Ecosystem respiration (R_e) also increased but less than GPP (from 20.2 to 28.3 Mg CO₂ ha⁻¹), thus resulting in an overall increment of NEE, which almost doubled in the third year compared to the establishment year (Table 3).

Fingerprint plot (Figure 5) allows visualizing the seasonal and daily patterns of CO₂ capture by the ecosystem

TABLE 3 Cumulative gross primary production (GPP), ecosystem respiration (R_e), net ecosystem exchange (NEE) and net ecosystem carbon balance (NECB) for each of the 4 years of experimentation. NECB is the difference between NEE and the C removed with harvested biomass

Year (April–March)	GPP Mg CO ₂ ha ⁻¹	R_e	NEE	NECB	Harvested C Mg/ha
2012–2013 ^a	-44.1	29.1	-14.9	-4.8	2.8
2013–2014	-61.7	34.7	-26.9	-7.9	5.2
2014–2015	-65.0	36.1	-28.9	-13.5	4.2
2015–2016	-57.2	32.2	-25.0	-7.2	4.9

Note. ^aFirst-year measurements started in May.

(NEE): the darker the color, the higher the C storage; the larger the blue area, the higher the C stored. Daily and seasonal patterns of NEE differed over the 4 years. Higher uptake of CO₂ was mostly in 2014, followed by 2013, 2015 and 2012. Within the same day, as expected, NEE was usually higher at midday, then decreased until a release of CO₂ that generally occurred from 6 p.m. to

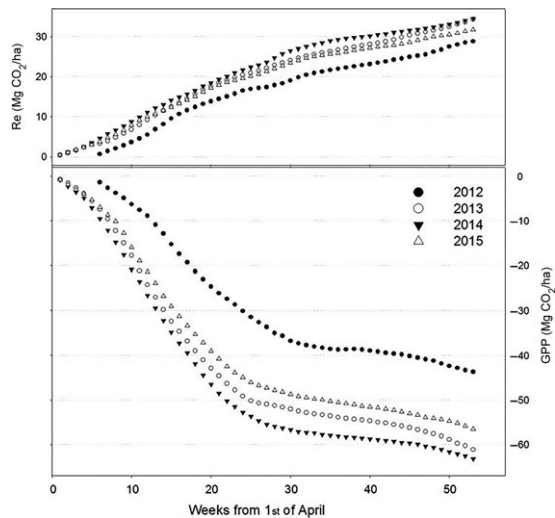


FIGURE 4 Cumulated gross primary production (GPP) and ecosystem respiration (R_e) in the 4 years of switchgrass cultivation. Values refer to daily cumulative fluxes; negative values indicate atmospheric CO_2 uptake by the ecosystem while positive values indicate CO_2 emission

6 a.m. (2 p.m. to 9 a.m. during wintertime). In 2012, NEE was limited but not negligible.

Cumulated monthly values of NEE (Figure 6) clearly showed that the difference between the establishment year and the following years was higher than $4 \text{ Mg CO}_2 \text{ ha}^{-1}$ at the beginning of the vegetative season, but that it decreased as the switchgrass reached maturity, until reaching similar levels in September. Maximum CO_2 monthly rate accumulation was $8.1 \text{ Mg CO}_2 \text{ ha}^{-1}$ in June 2013 (Figure 6).

3.4 | Aboveground biomass and net ecosystem carbon balance

Total harvested (mechanically) aboveground biomass (dry weight) was 6.9, 13.0, 10.5 and $12.1 \text{ Mg ha}^{-1} \text{ year}^{-1}$ in 2012, 2013, 2014 and 2015, respectively. From the second year on, yields reached the same biomass yield level of a nearby established switchgrass field in a hilly area, which production ranged from 7.9 to 11.3 Mg/ha (Di Virgilio, Monti, & Venturi, 2007). It should be recognized, however, that these values are an underestimation of the “canopy net accumulation rate” as not all biomass was recovered by the baling machine. About 1.2, 3.6, 5.3 and $3.6 \text{ Mg (d.w.) ha}^{-1}$ were measured as residual biomass left on the field after baling in 2012, 2013, 2014 and 2015, respectively. Harvest biomass losses were higher in 2014 due to lodging. The amount of aboveground biomass removed after harvest ranged from 66 (2014) to 85% (2012), while the amount of C removed from the ecosystem with harvests ranged from 53 (2014) to 71% (2015) of the NEE. The NEE can be subtracted of the C removed with harvested biomass to define

the net ecosystem carbon balance (NECB; Chapin et al., 2006), which represents an indication of the sequestered CO_2 (in the litter biomass, root biomass or SOC). NECB was negative in all years increasing from -4.8 to $-13.5 \text{ Mg CO}_2 \text{ eq ha}^{-1}$ from 2012 to 2014 ($-7.2 \text{ Mg CO}_2 \text{ eq ha}^{-1}$ in 2015) (Table 3). The 4-year cumulative NECB was $-33.4 \text{ Mg CO}_2 \text{ ha}^{-1}$. Over the last 3 years, mean NECB was $-9.5 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$, thus 98% higher than in the establishment year.

In November 2015, after four growing seasons, switchgrass root biomass in the upper 0.45 m soil layer was 8.35 Mg/ha , while cumulative (4 years) litter biomass on the ground was 12.7 Mg/ha . The C content of switchgrass fresh material was 41.1 ± 1.8 and $40.3 \pm 3.5\%$ (below- and aboveground biomass, respectively). We, therefore, estimated that 94% of the NECB was stocked into these two C pools, and only the remaining 6% was sequestered as SOC ($0.14 \text{ Mg ha}^{-1} \text{ year}^{-1}$). The sampling depth adopted was considered sufficient to factor in the majority of roots and SOC deposition as the measured SOC change between June 2012 and November 2015 corresponded to $0.13 \text{ Mg ha}^{-1} \text{ year}^{-1}$. However, considering the evolution of ^{13}C abundance in the soil, it was calculated that, after four growing seasons, switchgrass-derived SOC corresponded to 9.45 Mg/ha .

3.5 | Life cycle global warming potential

Considering 10 years of life span for the switchgrass stand, annualized emissions from the use of agronomic inputs were $733 \text{ kg CO}_2 \text{ eq ha}^{-1} \text{ year}^{-1}$. Nitrogen fertilization and harvest operations (cutting and baling) impacted most on emissions (23% and 60% of total emissions, respectively; Supporting information Table S1).

The displacement of fossil fuels produced CO_2 credits corresponding to $-5.7 \text{ Mg ha}^{-1} \text{ year}^{-1}$, after switchgrass harvested biomass was converted in advanced ethanol.

Simulated N_2O emissions resulted low (0.4 – $1.0 \text{ Mg CO}_2 \text{ eq ha}^{-1} \text{ year}^{-1}$, respectively in the establishment year or in the following years) compared to the ecosystem CO_2 uptake.

3.6 | Fluxes of water and water components

Similar ETC patterns were observed over the first 3 years, while in the fourth year ETC was significantly lower, likely due to a summer drought (Figure 2).

Evapotranspiration increased until May and started to decline from late June, and significantly decreased from July, in parallel with GPP and NEE. Other studies showed ETC to decline later in the season, for example in August (Skinner & Adler, 2010). In our study, ETC started to

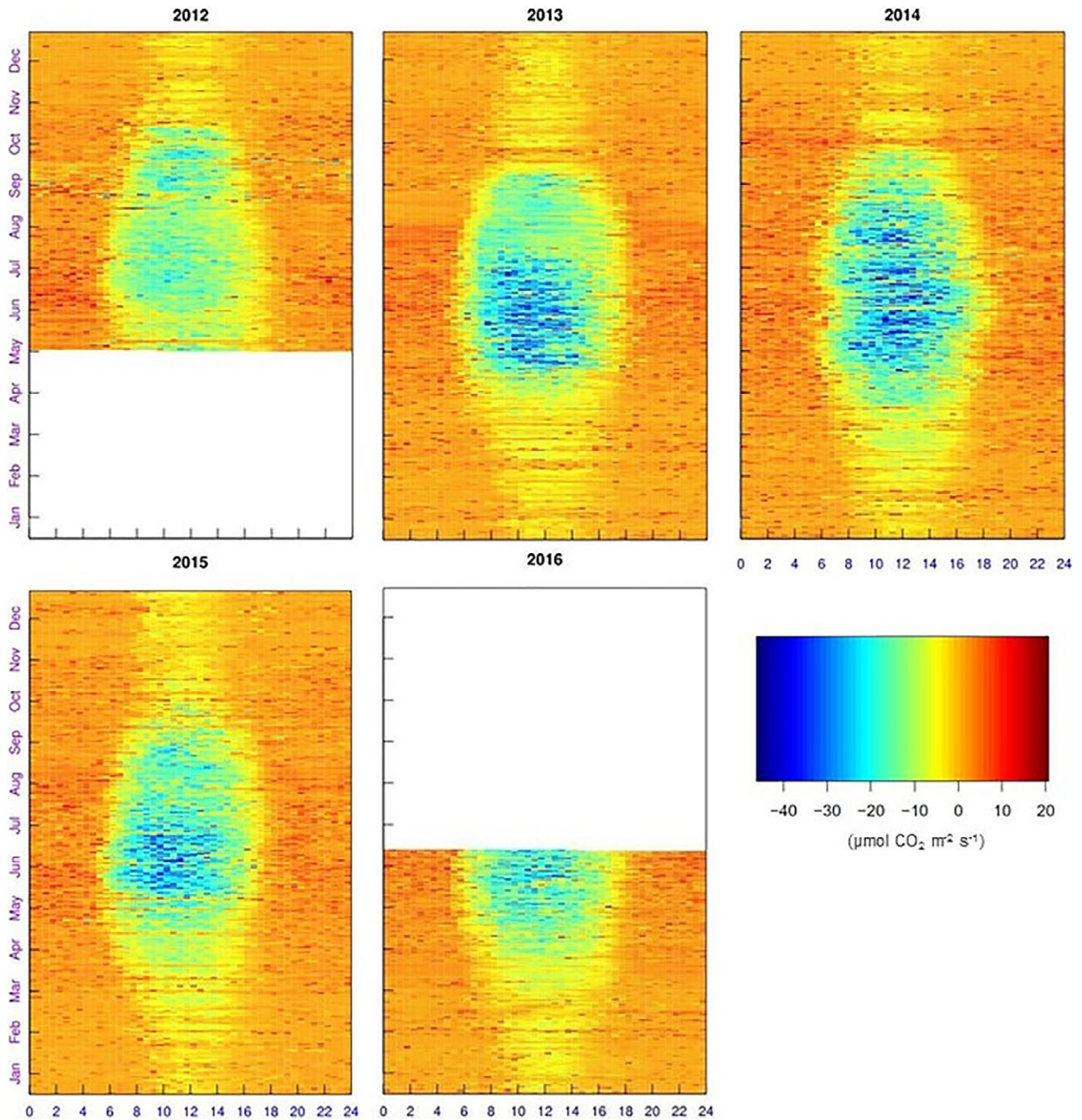


FIGURE 5 Fingerprint plot of net ecosystem exchange gap-filled values ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) with daily (x -axis) and seasonal patterns (y -axis) from May 2012 to June 2016; negative values indicate atmospheric CO₂ uptake by the ecosystem while positive values indicate CO₂ emission

decrease in August only in the establishment year. Average monthly ETc during the growing season ranged from 39.6 (2015) to 59.1 mm (2014). Cumulative annual ETc accounted for 55%, 56%, 59% and 50% of the annual precipitation (Table 2), respectively in the 4 years, in agreement with other studies (Abraha et al., 2015; Skinner & Adler, 2010). December showed the lowest cumulative ETc: 5.5, 8.1, 7.7 and 4.2 mm, respectively in the 4 years.

In this work, WUE was calculated by taking into account NEE and measured ETc (Table 5). Average WUE (ratio between NEE and ETc) was 1.3 (2012), 1.5 (2013), 1.6 (2014), 2.0 (2015) $\text{mg C g}^{-1} \text{ H}_2\text{O}$, with highest values occurring in August 2012, June 2013, June 2014 and July 2015 (2.3, 2.5, 2.7 and 10.5 $\text{mg C g}^{-1} \text{ H}_2\text{O}$, respectively). ETc was particularly low in July and August 2015, resulting in a decreased CO₂ uptake (Table 3) but also in a

much higher WUE for that period. Decreased ET_c in summer 2015 could be the result of a prolonged lack of moisture in the soil (Table 2). NEE and GPP resulted significantly correlated with ET_c ($r^2 = 0.45^*$ or 0.48^* , respectively; all years' growing season daily data).

Moreover, considering the estimated use of water during transformation to ethanol ($0.5 \text{ Mg H}_2\text{O GJ}^{-1}$; Berndes, 2002) and the evapo-transpired water during the growing season (April–October), WUE of ethanol production corresponded to 0.95, 0.71 and $1.22 \text{ L (EtOH) Mg}^{-1} \text{ H}_2\text{O}$, respectively in 2013, 2014 and 2015. However, almost all the consumed water (about 99%) was part of that received by the crop during the cultivation phase from rainfall.

4 | DISCUSSION

Despite a considerable lower biomass accumulation in the first year, switchgrass was however able to maintain a CO₂ storage capacity in all years. Mean NEE and NECB of switchgrass during the postestablishment years (second to fourth year) were -26.9 and $-9.5 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$, respectively, with NEE reaching peak monthly values of -8.1 , -7.9 and $-7.6 \text{ Mg CO}_2 \text{ ha}^{-1}$ during the 2013, 2014 and 2015 growing seasons, respectively. In the same way, in a semiarid environment in Oklahoma, Wagle and Kakani (2014) measured a peak monthly value of NEE in a young switchgrass stand of $-9.9 \text{ Mg CO}_2 \text{ ha}^{-1}$. Different from the present study, they estimated that NECB made switchgrass a small C source; nevertheless, their monitoring was limited to the establishment period. Lower values of yearly NECB ($-1.4 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$) were reported by Skinner and Adler (2010) in a study in Pennsylvania under a continental climate and at higher altitude than our experimental site. Studies in Iowa (Al-Kaisi, Yin, & Licht, 2005) and in South Dakota (Lee, Owens, & Doolittle, 2007) reported SOC sequestration rates by mature stands from -4.4 to $-14.7 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$, while in the Central Illinois (Zeri et al., 2011), having the same latitude as in the present study, switchgrass C sequestration (NEE) was $-9.0 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$ in the first year to then steeply increase in the second and third years (-16.6 and $-17.8 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$, respectively), in line with our findings, although lower. As reported in Skinner and Adler (2010) and Zeri et al. (2011), a stabilization of switchgrass yields and NEE to higher values starting from the second year was also observed in this study. This is an indication that establishment of switchgrass might be faster than in other bioenergy perennial crops such as miscanthus (*Miscanthus × giganteus* Greef and Deuter) and giant reed (*Arundo donax* L.).

Starting from late March/early April, R_e tended to increase (Figure 4), together with increasing air and soil

temperatures. A major determinant for R_e was in fact the air temperature ($r^2 = 0.62^{**}$, data not shown). Lower values of R_e were recorded in this study (24.7 – $33.4 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$; Table 3) than measured elsewhere for other switchgrass stands (29.1 – $36.1 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$; Skinner & Adler, 2010), which could be linked to lower soil temperatures (Bremer, Ham, Owensby, & Knapp, 1998). Observing how R_e seems strongly related to air temperature suggests that further studies in warmer climates of the southern Mediterranean are needed.

Gross primary production also increased every year from late March showing a similar pattern to R_e (Figure 4). In the establishment phase, GPP was considerably lower than in the following years. While in the last 3 years the highest GPP occurred in June, in the first year it occurred in July, thus 1 month later (Figure 4). Switchgrass was reported to maximize the photosynthetic rate in the range of 30 – 35°C (Zeri et al., 2011). As this range was recorded only in 2012, GPP might have been limited by temperatures in the following 3 years. However, although lower than measured by Zeri et al. (2011; ~ -51 to $-80 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$), GPP measured at our site (-44.1 to $-65.0 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$; Table 3) was substantially higher than recorded in other studies on switchgrass (Skinner & Adler, 2010; Wagle & Kakani, 2014).

The ecosystem C assimilation (negative NEE) lasted 176 (from May), 182, 226 and 185 days, from first to fourth year, respectively, which is a considerable longer period than that measured by Skinner and Adler (2010) or by Zeri et al. (2011) in the northern United States (98 and 90 days, respectively). The NEE usually turned negative in the second half of March (earlier in 2014, at the end of February) and stayed negative until October. In an important way, CO₂ assimilation rates (GPP) were still substantial at the time of harvest, suggesting that it could be delayed to the end of October in order to exploit a longer accumulation period.

Concerning the C partition of NEE by measuring the C content of the above-, belowground biomass and soil in the switchgrass stand, our results seem to confirm that most of the C storage occurred in the upper soil (0 – 0.45 m). This is in agreement with previous studies (Garten & Wullschlegel, 2000; Qin et al., 2016), although also depending on the specific land-use history of the experimental site.

Switchgrass-derived SOC in four growing seasons corresponded to 9.45 Mg/ha . Given the net SOC change in four growing seasons (0.52 Mg/ha), it derives that about 8.9 Mg/ha of older SOC (C3-derived) was lost by the ecosystem, and this emission corresponded to the 27% of total R_e from establishment to the end of the fourth growing season (November 2015). In an interesting manner, in a nearby long-term switchgrass trial where the former crop

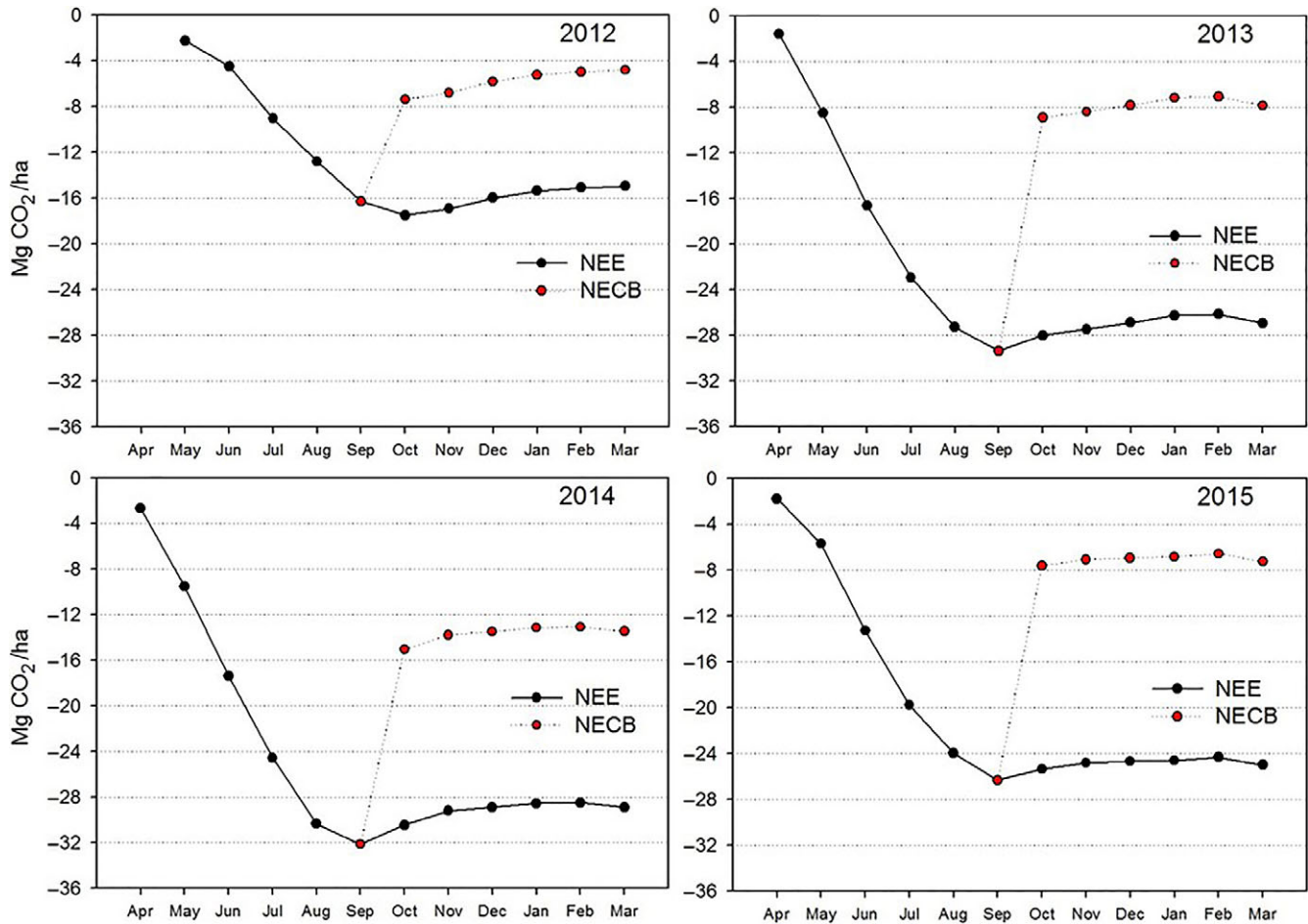


FIGURE 6 Cumulated net ecosystem exchange (NEE) and cumulated net ecosystem carbon balance (NECB) in the 4 years of switchgrass cultivation. NECB represents the NEE discounted by the carbon removed with biomass harvest; the lower the values the higher the CO₂ uptake by the ecosystem

had been poplar (*Populus* spp.; Nocentini & Monti, 2017), different SOC dynamics were observed, likely due to distinct land-use change effects. In the first 3 years after poplar conversion into switchgrass, poplar-derived SOC increased by 0.15 g kg⁻¹ year⁻¹ while the increment in switchgrass-derived SOC was insignificant (Nocentini & Monti, 2017), because of the persistence of poplar residues. On the contrary, in the present study, residues from annual crops were largely emitted in the first 3 years after conversion into switchgrass, allowing a substantial switchgrass-derived SOC deposition (in November 2015, 14% of total SOC was switchgrass-derived). The net SOC increase was quite low in the first years of switchgrass production, nevertheless it should be taken into account that the soil C stock at establishment was substantial (67.0 Mg/ha in the top 0.45 m), likely due to the residue management normally applied at the experimental farm (i.e. annual crops' residue reintegration) combined with the fine texture of the soil which tends to bind organic matter more strongly and thus stabilize it more compared to sandy textured soils (Parton, Schimel, Cole, & Ojima, 1987).

After 4 years of cultivation, most of the sequestered C (94%) was then still stocked into the more biochemically active litter and root pools. Nevertheless, these C pools will, more or less substantially, contribute to SOC in the following years or when, after 10 years, the soil will be tilled before restarting a new switchgrass (or other perennial crop) cycle (during which new litter and root C pools are going to form). Indeed, even before tillage, litter can be incorporated into the soil by the activity of the microfauna (Agostini, Gregory, & Richter, 2015), and, further, in perennial herbaceous systems, coarser roots can persist in the soil for years before being mineralized, so that their incorporation into the SOC pool can occur when the stand is already mature (Agostini et al., 2015).

Life cycle CO₂ emission was estimated -12.4 Mg CO₂ eq ha⁻¹ year⁻¹ in the first 4 years of switchgrass cultivation. This is a very high CO₂ reduction potential if compared to similar studies (Gelfand et al., 2011, 2013; Skinner & Adler, 2010; Zenone et al., 2013; Zeri et al., 2011), although its higher significance can be

TABLE 4 Summary of Life cycle CO₂ emission from a farm-scale switchgrass stand in North Italy monitored for four consecutive years. The net ecosystem C balance (NECB) was measured by an eddy-covariance system and by carrying out biomass harvest every year. N₂O emissions were estimated with the DAYCENT model. Emissions from agronomic input use were estimated using a dedicated software (SimaPro 8.0). Fossil fuel offset credits were calculated applying a literature coefficient to the switchgrass productions registered at the experimental farm

	CO ₂ emission (Mg ha ⁻¹ year ⁻¹)
NECB	-8.35
N ₂ O emission	0.88
Agronomic inputs use	0.73
Fossil fuel offset	-5.69
Life cycle	-12.43

Life cycle CO₂ emission corresponds to the sum of NECB, N₂O emission, agronomic input use and fossil fuel offset (in bold).

largely explained by the high biomass production and, more in general, by the high sink capacity (NEE) attained by switchgrass in the present study. The main reasons for the discrepancy are likely the longer growing season and accumulation potential in the warmer Mediterranean environment and the land-use change from annual food crops. For example, Skinner and Adler (2010) and Zeri et al. (2011) measured less than 100 days with continuous negative NEE in the northern USA, while, at Cadriano site, on average, switchgrass acted as a net sink for 198 days in a row. If excluding the establishment year, mean biomass harvest yields at Cadriano site were 11.9 Mg ha⁻¹ year⁻¹, while they were 4.9 and 5.6 Mg ha⁻¹ year⁻¹ in Skinner and Adler (2010) and Zenone et al. (2013), respectively. In Zeri et al. (2011) aboveground biomass yield of switchgrass was high (11.5 Mg ha⁻¹ year⁻¹) and, similarly to the present study, the measured NECB was -7.3 Mg CO₂ ha⁻¹ year⁻¹; also in their study switchgrass was cultivated after the former land-use was annual food crops (oats). Gelfand et al. (2013) measured aboveground yields of about 15 Mg ha⁻¹ year⁻¹ for their successional grass system and their estimation of life cycle GHG emission is slightly lower than found here (-9.2 Mg CO₂ eq ha⁻¹ year⁻¹), as the fossil fuel offset credits were over 6 Mg CO₂ eq ha⁻¹ year⁻¹, but the NECB was not as impactful (-4.0 Mg CO₂ ha⁻¹ year⁻¹), although significant; in their study the land-use change was from unmanaged marginal lands, thus the potential to accumulate ecosystem C lower. Zenone et al. (2013) included a scenario where switchgrass followed annual crops, but, surprisingly, in their study this land-use change produced CO₂ emissions rather than acting as sink (NECB = 5.5 Mg CO₂ ha⁻¹ year⁻¹), even after including fossil fuel offset credits in the balance (4.1 Mg CO₂ eq ha⁻¹ year⁻¹). At

their site switchgrass harvested biomass was low, probably due to a slow establishment phase and, however, their measurement were limited to the first 2 years of switchgrass. Furthermore, in Zenone et al. (2013) the land had been converted to a corn-soybean rotation in the last few decades before land-use change to switchgrass, whereas it had been a grassland, probably accumulating high C stocks, before then.

Our estimated emission from agronomic inputs use (733 kg CO₂ eq ha⁻¹ year⁻¹) is in line with previous studies in the same region (686 kg CO₂ eq ha⁻¹ year⁻¹; Fazio & Monti, 2011), and with studies carried out elsewhere (635 kg CO₂ eq ha⁻¹ year⁻¹; Gelfand et al., 2013).

Although not insignificant, estimated N₂O emissions (0.9 Mg CO₂ eq ha⁻¹ year⁻¹) did not have a substantial impact on the Life cycle GHG balance of switchgrass (Table 4). Also, Skinner and Adler (2010) reported low N₂O emissions in switchgrass ranging from 0.3 to 0.5 Mg CO₂ eq ha⁻¹ year⁻¹, thus slightly influencing NEE. This was also confirmed by Don et al. (2012) that found perennial biofuel grasses to emit 40%–99% less N₂O than annual cropping systems.

Methane (CH₄) emission was not assessed in this study, but it was found to have a very limited impact on Life cycle GHG emission of biofuel perennial systems (Gelfand et al., 2011, 2013).

The present study did not include ILUC emissions in switchgrass GHG balance, as their estimation is uncertain (Plevin et al., 2010). If adopting the factors and formulas from Plevin et al. (2010) and using our estimated switchgrass ethanol yields, ILUC emissions would vary between 13 and 456 g CO₂ MJ⁻¹, thus from very low to highly impactful. Nonetheless, Zilberman (2017), in a recent commentary, using empirical evidence based on history, argued that ILUC might just be “much ado about (almost) nothing.” Moreover, given the progressive abandonment of cropland observed in Europe in the last decades (Ramanakutty & Foley, 1999), it can be hypothesized that converting marginal cropland to switchgrass in the Mediterranean might not generate much ILUC effect.

Regarding water use, almost 60% of annual precipitation was used by the crop, while most of the ET_c (up to 93%) occurred within the growing season only (Table 2). Hence, switchgrass growth was apparently not limited by water availability. It should also be noted that the mean annual depth of the water table in this area is 140 cm, thus quite shallow. This gives the possibility to a deep-rooted crop such as switchgrass to use the belowground water reserve if facing short drought periods (Abraha et al., 2015).

Measured WUEs were higher than WUEs observed in miscanthus or giant reed in the Mediterranean area (Triana, Nasso, Di Nasso, Ragagnoli, Roncucci, & Bonari, 2014), two perennial lignocellulosic crops of commercial interest

TABLE 5 Correlation factors between cumulative evapotranspiration (ETc) and net ecosystem exchange (NEE) or gross primary production (GPP). ETc-to-NEE ratio indicates the amount of evapo-transpired water for the net fixation of CO₂ at ecosystem level, and ETc-to-GPP ratio indicates the amount of evapo-transpired water for the absorption of CO₂ by the ecosystem

Year	ETc per NEE (m ³ H ₂ O Mg ⁻¹ CO ₂)	r ²	ETc per GPP (m ³ H ₂ O Mg ⁻¹ CO ₂)	r ²
May–October 2012	171	0.33	79	0.58
April–October 2013	137	0.75	73	0.73
April–October 2014	138	0.62	73	0.61
April–October 2015	110	0.18	57	0.19

that could compete with switchgrass for the same land. A correlation between CO₂ uptake (GPP, NEE) and ETc was found. A strong correlation in switchgrass was also found by Skinner and Adler (2010) between GPP and ETc ($r^2 = 0.87$). The linear correlation of ETc with NEE and GPP (Table 5) suggested a strong linkage between C fixation and water loss over the seasons.

The results from this study can provide a strong base to estimate potential environmental benefits of the large-scale deployment of switchgrass in the Mediterranean region. Nocentini et al. (2015), using the Corine Land Cover database (European Environment Agency, 2010), estimated that 1.21 Mha of marginal cropland might be used for switchgrass cultivation in the Mediterranean. It is assumed here that most of the marginal cropland identified by Nocentini et al. (2015) had been, as the experimental site in this study, under arable land use for many decades, as, opposite to agricultural expansion, a progressive abandonment of cropland in Europe (and the Mediterranean; Greco & Bellini, 2010) has been observed since the 1960s (about 20 Mha of abandoned cropland; Ramankutty & Foley, 1999), mainly in marginal areas (Hatna & Bakker, 2011). Hence, if we hypothesize $-12.4 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$ absorbed during switchgrass life cycle, switchgrass could potentially capture, in the whole region, 15.0 Mt CO₂ during each year after establishment. Ten years of switchgrass production (i.e. the economic life span normally considered for a switchgrass stand) may therefore offset EU's CO₂ equivalent emissions ($4,451.8 \text{ Mt CO}_2 \text{ year}^{-1}$; EUROSTAT, 2015) by 0.33% every year; this value is highly relevant if weighted on the 20% reduction goal set by EU for the period 1990–2020 (Delbeke & Vis, 2016). Nonetheless, it must be considered that this is likely an overestimation as the NECB and ethanol yields might reduce in time due to ecosystem carbon saturation and stand maturation, especially between the sixth and tenth year of production (Arundale et al., 2014; Eichelmann, Wagner-Riddle, Warland, Deen, & Voroney, 2016; Nocentini et al., 2015). In a possible scenario, switchgrass ecosystem may have reached C equilibrium at the fourth year, so that from the fifth to the tenth years of cultivation the NECB factor would equal zero in the life cycle balance, and this would reduce the

life cycle emission to $-7.4 \text{ Mg CO}_2 \text{ eq ha}^{-1} \text{ year}^{-1}$ and the EU's GHG reduction to 0.20% every year. If this is true, at the same time, more CO₂ would probably be saved, if considering the foregone emission of the former annual crops cultivation (i.e. higher emission from agronomic inputs and higher N₂O emissions) compared to switchgrass perennial system to which it was converted (Adler et al., 2007; Don et al., 2012; Fazio & Monti, 2011). At last, although highly uncertain (Plevin et al., 2010) and unlikely to be very impactful in the “old” Europe (Zilberman, 2017), especially after marginal cropland conversion (Hatna & Bakker, 2011; Ramankutty & Foley, 1999), ILUC emissions could totally offset the GHG benefits brought by switchgrass large-scale cultivation in Mediterranean marginal cropland. Therefore, more accurate methods to determine ILUC are necessary as soon as possible, although not yet at the horizon (Plevin et al., 2010).

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SUPPORTING INFORMATION

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