Received: 27 January 2022 | Accepted: 21 February 2022

DOI: 10.1111/gcbb.12944

GCB-BIOENERGY
BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY
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RESEARCH ARTICLE

Is switchgrass good for carbon savings? Long-term results in marginal land

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Funding information
FP7 Food, Agriculture and Fisheries, Biotechnology, Grant/Award Number: OPTIMA project (GA 289642); H2020, Grant/Award Number: MAGIC project (GA 727698)

Abstract

The cultivation of perennial crops in marginal land as a feedstock for renewable energy or bio-based products constitutes a promising alternative to mitigate greenhouse gas emissions since they can be produced without land competition issues and with potentially significant amounts of belowground C storing. The objective of this study was to assess soil C storage capacity of switchgrass on a marginal land (poor soil with limited rooting depth on a hilly area) through a spatialized analysis derived from several soil samples. A significant increase in SOC was observed after 13 years. In general terms, SOC increased by 12 Mg C ha^{-1}. The estimated switchgrass-derived C was 12.7 (±5.3) Mg C ha^{-1}. A significant positive correlation was observed between the C derived from switchgrass and SOC gain. The increased SOC along the field, however, was patchy, with the highest increments registered in the center of the field, while the lowest ones in the top and bottom of the hill. Soil N stocks have also increased along with the soil C storage, although no direct relationship with C derived from switchgrass was observed. Therefore, it could be stated that growing switchgrass in marginal land can be a valuable option to mitigate the risk of agricultural land abandonment while storing a significant amount of soil C.

KEYWORDS

advanced biofuels, bioenergy, bioethanol, greenhouse gas emissions, lignocellulosic feedstock, limited rooting depth, perennial crops, stable isotopes

1 | INTRODUCTION

The increase of the greenhouse gas (GHG) emissions needs the adoption of global strategies for their mitigation in order to reduce the C footprint of anthropic activities, among others agriculture represents one of the main causes (Babur et al., 2021; Battaglia et al., 2020; Smith et al., 2008). Perennial bioenergy crops can significantly contribute to this objective by sourcing advanced biofuels capable of partially replacing fossil fuels, as well as being able to sequester relevant amounts of C in the belowground (Martani et al., 2021). Additionally, bioenergy crop cultivation in marginal land has gained increasing attention being able to meet energy production coupled

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with undisputable additional ecological benefits, particularly when managed with optimized input use, without displacing food crops from the most productive lands, thus avoiding iLUC (indirect land use change) (Dauber et al., 2012; Skinner et al., 2012; Stoof et al., 2015; Valentine et al., 2012; Von Cossel, Lewandowski, et al., 2019). In this scenario, perennial bioenergy crops typically produce both higher aboveground and belowground biomass and have lower management costs than annual ones, with relevant ecological functions such as the reduction of soil erosion, the improvement in water quality, and the enhancement of wildlife habitat, and consequent indisputable positive socioeconomic drawbacks (Roth et al., 2005; Scordia & Cosentino, 2019; Von Cossel, Wagner, et al., 2019). This is behind the strategy adopted by the European Commission to target marginal soils as the ones where to promote the cultivation of bioenergy perennial crops (Elbersen et al., 2017; Fernando et al., 2015), to produce low iLUC risk feedstock for energy purposes.

Among other candidate lignocellulosic perennial crops, switchgrass (*Panicum virgatum* L.) seems one of the most promising, mainly in relation to lower costs of management since it is easily propagated by seeds, differently than alternative biomass crops, such as miscanthus (*Miscanthus sp.*) and giant reed (*Arundo donax* L.). Additionally, the availability of upland and lowland ecotypes, suitable for different growing environments (Casler et al., 2004; Zegada-Lizarazu et al., 2012), and the outstanding capacity of forming an extensive root system, also in depth (Alexopoulou et al., 2020; Martani et al., 2021; Monti & Zatta, 2009), make switchgrass a perfect candidate for being an interesting bioenergy crop for Europe, also in case of marginal soils (Slessarev et al., 2020; Zegada-Lizarazu et al., 2010). In fact, perennial grasses are often deeply rooted and able to offer high yearly net primary productivity coupled with the capability to increase soil organic carbon (SOC) (Martani et al., 2021; Kumar, Lai, Battaglia, et al., 2019; Kumar, Lai, Kumar, et al., 2019; Zegada-Lizarazu et al., 2010). Increased C sequestration by perennial grasses is explained by their higher C input from roots (lower shoot/root ratio) (Bolinder et al., 2007; Monti & Zegada-Lizarazu, 2016) and the reduced soil disturbance that typically occurs in perennial systems (Post & Kwon, 2000). Switchgrass is a C4 species, and it is possible to use naturally occurring C isotopes (^{13}C, ^{14}C) to trace C fluxes (Jones & Donnelly, 2004) from atmosphere to soil, and for instance ^{13}C is commonly used to quantify the fraction of SOC derived from recent plant inputs.

An increase in SOC stocks can reduce carbon dioxide (CO_2) emissions from soils through C sequestration, while also improving overall soil quality (Blanco-Canqui, 2010). Nevertheless, when operating in marginal soils, these positive features might be significantly impaired by the growing environmental conditions and consequently the actual capability of switchgrass to promote soil quality could be significantly reduced, due to limited above and belowground biomass growth. Furthermore, marginal soils are often intrinsically characterized by large spatial variability for characteristics such as soil texture, physical–chemical properties, slopes, etc. (Di Virgilio et al., 2007), thus making the estimation of the environmental benefits derived from perennial crops very challenging. One of the main approaches to make such estimations is to adopt models (Martinez-Feria & Basso, 2020), while very limited research has been conducted on spatially explicit quantification of soil quality changes and soil C sequestration at field level for such crop. At this scope, in the present study, the impact of switchgrass on soil quality (i.e., SOC, pH, N, and P content in lieu of improved soil physicochemical characteristics) has been assessed by a spatialized analysis derived from several soil samples taken in a hilly area at 3 years after the establishment of the stand (2005) and at the end of its productive life span (2015), thus providing reliable data on the spatial variability of the C sequestration capacity of switchgrass grown in a marginal soil.

2 | MATERIALS AND METHODS

2.1 | Field trial description

A large switchgrass field trial was established at the experimental farm of the University of Bologna in Ozzano dell'Emilia (44°25′N; 11°28′E, 80 m a.s.l.), on a surface area of 4.8 ha, where the previous crop was sugar beet (*Beta vulgaris* L.). The test area is in the hilly surrounding of Bologna, Italy (Apennine Mountain chain), and the experimental field has variable slope ranging from 2% to 10%. According to the Koppen–Geiger classification, the climate is a typical Mediterranean with the highest and lowest temperatures in July and December, respectively, and the rainy periods concentrated in spring and fall. In summer, short storms provide significant water input with high erosive potential (Pieri et al., 2014). From the characterization of the site carried out in 2004, and thoroughly reported by Di Virgilio et al. (2007), the soil was classified as loam, clay-loam, and silty-clay-loam (USDA classification) with an average content of sand, silt, and clay of 33.2%, 36.9%, and 29.9%, respectively, in particular sand content was found often above 40% across the field. The soil pH was 7.9, and the OM content ranged between 0.83% and 1.60%, reporting an average value of 1.27%. Besides that, the soils presented low contents of P (10 ± 23 mg kg^{-1}) and N (10 ± 1 mg g^{-1}), and limited rooting depth due to heavy soil compaction (soil strength 1.8 ± 0.3 MPa; root elongation of several species

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is typically affected with soil penetration resistance of >0.8–2 MPa; Correa et al., 2019). The combination of all the above mentioned soil characteristics allows authors to use the definition of marginal soils by combination of different sub-severe biophysical constraints, as stated by JRC (JRC Report 92686, 2014). Sowing took place in May 2002, and the lowland variety Alamo was sown at a density of about 10 kg ha^{-1} pure lived seeds. The full description of the trial establishment and agronomic management is reported by Di Virgilio et al. (2007). Every year, from 2002 until 2015 in late autumn or early winter, the switchgrass aboveground biomass was mechanically harvested, windrowed, and then baled to determine the total biomass production. The last harvest was in autumn 2015 when the production of the switchgrass stand dropped below 4 Mg DM ha^{-1} and the experiment was considered completed.

2.2 | Soil sampling and characterization

The experimental field was fully characterized in 2007 (Di Virgilio et al., 2007). In order to assess the effects of a switchgrass stand on the main soil characteristics after 13 years, a new set of soil samples was taken in winter 2015 (just after the last harvest of switchgrass) adopting a similar approach as described by Di Virgilio et al. (2007). In short, 35 soil cores, regularly distributed across the field (from the top to the bottom of the hill), were sampled manually by means of a soil core down to a depth of 0.3 m and georeferred with GPS device (GEKO 201, Garmin, Ltd.). Each soil sample was air-dried and coarse roots were removed by passing the soil through a fine sieve of 2 mm before being ground for chemical analysis. The analyzed soil parameters were as follows: pH, organic C (g kg^{-1}), OM (%), total N (g kg^{-1}), and available P_2O_5 (mg kg^{-1}). The methods adopted for soil characterization are reported in Table 1. Additionally, C_4 SOC gain was estimated from the fraction of soil C derived from switchgrass (SGd) and was calculated as follows:

TABLE 1 Soil parameters and methods utilized for their evaluation at the beginning and end of the switchgrass trial (2005–2015)

Parameter	Method	Unit
pH	Measured in water	—
Organic carbon	Walkley-Black (Walkley, 1947)	g kg^{-1}
OM	Walkley-Black (Walkley, 1947)	%
Total N	Dumas (Dumas, 1831)	g kg^{-1}
Available P_2O_5	Olsen (Olsen et al. 1954)	mg kg^{-1}
Exchangeable K_2O	Dirks and Scheffer (AOAC, 1990)	mg kg^{-1}

$$\mathrm{SGd} = \left[\left(\delta^{13}\mathrm{C\ observed} - \delta^{13}\mathrm{C\ SOC\ initial} \right) / \left(\delta^{13}\mathrm{C\ switchgrass\ plant\ tisssue} - \delta^{13}\mathrm{C\ SOC\ initial} \right) \right] \times \mathrm{Ct},$$

where SGd is the switchgrass-derived C; δ^{13}C observed is the soil ^{13}C abundance relative to ^{12}C after 13 years of switchgrass; δ^{13}C initial is the soil ^{13}C abundance relative to ^{12}C of a nearby reference field grown continuously with a C3 species (*Medicago sativa*; $\delta^{13}C = -25.69‰$) and therefore no change in the δ^{13}C initial value is assumed; δ^{13}C switchgrass plant tissue is the mean ^{13}C abundance relative to ^{12}C of switchgrass roots ($\delta^{13}C = -13.44‰$); and Ct is the total soil organic C. The organic C and ^{13}C of the different components were determined with the aid of a continuous flow–isotope ratio mass spectrometry (CF–IRMS, Delta V Advantage Thermo Scientific). For that purpose, about 12 mg of subsamples were pretreated (as in Tonon et al., 2010) with HCl and heated to 80°C to completely remove the carbonates. The ^{13}C values were expressed in delta units as

$$\delta^{13}\mathrm{C}‰ = \left[(\mathrm{Rsample} / \mathrm{Rstandard}) - 1 \right] \times 1000$$

where Rsample is the isotope ratio $^{13}C/^{12}C$ of the sample and Rstandard is the $^{13}C/^{12}C$ ratio of the international Pee Dee belemnite (PDB) carbonate standard. The total C stocks was calculated by multiplying the C soil concentration, soil bulk density, and depth layer. Bulk density was determined by a steel cylinder (Ø 48 mm) to collect vertical undisturbed soil cores, which were subsequently oven-dried at 105°C for 72 h to constant weight in six representative points along the filed. Bulk density was determined to be 1.38 and 1.30 g cm^{-3} before and after switchgrass establishment. The equivalent soil mass method (Ellert & Bettany, 1995) was applied to obliterate the variability of bulk density in SOC storage calculations.

2.3 | Spatial soil structure and map creation

Soil maps were created by the spatial interpolation of georeferred values of investigated soil parameters at the place of the sampling points. In function to the amount of sampling points available, inverse distance weighted (IDW) interpolation method (interpolation power of 2) was applied in Q-GIS software. This method assumes that each point has a local influence that decreases with distance. Since spotty samples were collected across the field, it was necessary to create continuous maps for each parameter to allow comparisons. A specific dataset was extracted on the base of the overlay of the same grid on all maps to understand the correlation between SOC spatial variability and other soil parameters. At each vertex, the interpolated

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value of the IDW map was assigned with the use of Q-GIS tools (Di Virgilio et al., 2007).

2.4 | Statistical analysis

The difference across years between the means of the sampling points was evaluated using a one-way analysis of variance (ANOVA). Soil parameters were also evaluated by descriptive statistics, and the relationships between C derived from switchgrass and selected soil parameters were evaluated using Pearson's correlation test.

3 | RESULTS

The average changes in time on the main soil chemical characteristics induced by a 13-year-old switchgrass plantation are presented in Table 2. Compared to 2005 (when switchgrass stand was 3 years old), a significant increase ($p \leq 0.05$) in C and total N concentrations was observed under the mature crop stand (2015); the increments were in the range of 0.3 and 0.2 g kg^{-1}, respectively. On the other hand, a significant reduction in extractable P was observed (−4.7 mg kg^{-1}), while the soil pH remained almost unvaried (with an average increase of 0.04 units).

The changes in SOC stock with time (2015–2005) and the estimated C derived from switchgrass in 2015 are shown in Figure 1. The SOC stock in 2005 was about 29 Mg C ha^{-1} while in 2015 increased up to 41 Mg C ha^{-1}, with an average increase of about 0.8 Mg C ha^{-1} year^{-1}. The derived C from switchgrass was 12.7 Mg C ha^{-1}. Moreover, the derived SOC from switchgrass was positively related to the increment of SOC stock from 2005 to 2015 ($r = 0.78^{**}$; Figure 2). On the other hand, no significant correlations were found between the derived switchgrass SOC and the changes in time of total N, and pH (Figure 2). As for the extractable P, a close negative relationship was found between P and C derived from switchgrass ($r = -0.42^{*}$; Figure 2).

TABLE 2 Soil chemical characteristics in a long-term switchgrass plantation

	pH	Total N (g kg^{-1})	P_2O_5 (mg kg^{-1})	Organic C (g kg^{-1})
2005	7.91	0.99	23.54	0.74
2015	7.94	1.23	18.86	1.04
Diff	0.04	0.24	−4.68	0.30
$p \leq 0.05$	ns	**	*	**
SE	±0.040	±0.032	±1.567	±0.037

Note: Asterisks indicate a significant change with time in the corresponding parameter (one-way ANOVA).

The maps of SOC stock, N, P, and pH changes in the 2005–2015 period are shown in Figure 3. SOC increments with time varied considerably across the field with the lowest values in the northern (top) and southern (bottom) parts of the hill, while the highest increments were registered in the center. The map of N changes (Figure 3) also shows a patchy increment distribution with the largest increments in the central part of the field (between 1.17 and 1.23 g N kg^{-1}), while the lowest increments were registered in the northern and southwestern parts of the hill. On the other hand, across almost all over the field, the extractable P decreased with time; only in the topmost part of the hill, a slight increase was registered (Figure 3). The highest increments in pH were again registered in the center of the field and decrements in the southwestern parts of the hill.

4 | DISCUSSION

The cultivation of switchgrass in marginal land demonstrated to be able to be a feasible strategy to improve soil quality. Compared to 2005 (when switchgrass stand was 3 years old), a significant increase ($p \leq 0.05$) in SOC was observed under the mature crop stand (2015). In general terms, SOC increased by 12 Mg C ha^{-1}, most of it deriving from switchgrass (Figure 1); in fact, the estimated C derived from switchgrass was 12.7 (±5.3) Mg C ha^{-1}, representing about 31% of the existing SOC in 2015. Moreover, a significant positive correlation ($r = 0.78^{**}$) was observed between the C derived from switchgrass and the SOC gain in the 2005–2015 period (Figure 2). The aforementioned SOC increase patterns could be partially explained by the large and well-developed root system of switchgrass. In fact for a lowland ecotype similar to Alamo (the subject of this study), root biomass accounted for 27% to 34% of the total plant biomass (Griffiths et al., 2022), representing between 5.9 and 7.6 Mg of root biomass per hectare (Frank et al., 2004; Griffiths et al., 2022). Switchgrass root biomass could represent twice as much the aboveground biomass in long-term plantations (Wilts et al., 2004). In addition to the large amounts of root biomass produced in the long term, Monti and Zatta (2009) showed that switchgrass develops a homogeneous and well-distributed root system up to 1.2 m depth, hence contributing to SOC accumulation along the soil profile. However, to the best of our knowledge, there are not long-term studies where switchgrass cultivated for more than 10 years in a marginal land accumulated large amounts of SOC in the top 20–30 cm of the soil. Therefore, it could be said that the reported increase in SOC (Figures 1 and 2) after 13 years of a switchgrass stand is a well-suited strategy to increase the aggregate stability, infiltration, drainage, and

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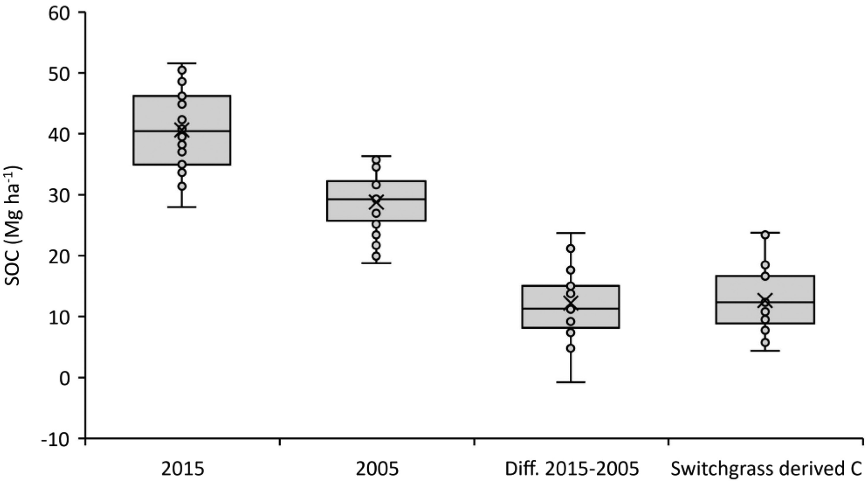

FIGURE 1 Soil organic carbon (SOC) changes with time (2015–2005) and estimated C derived from switchgrass in 2015. Boxes represent the proximate 25% and 75% quartiles and maximum and minimum values observed. X indicates the average values, and the solid horizontal line indicates the median

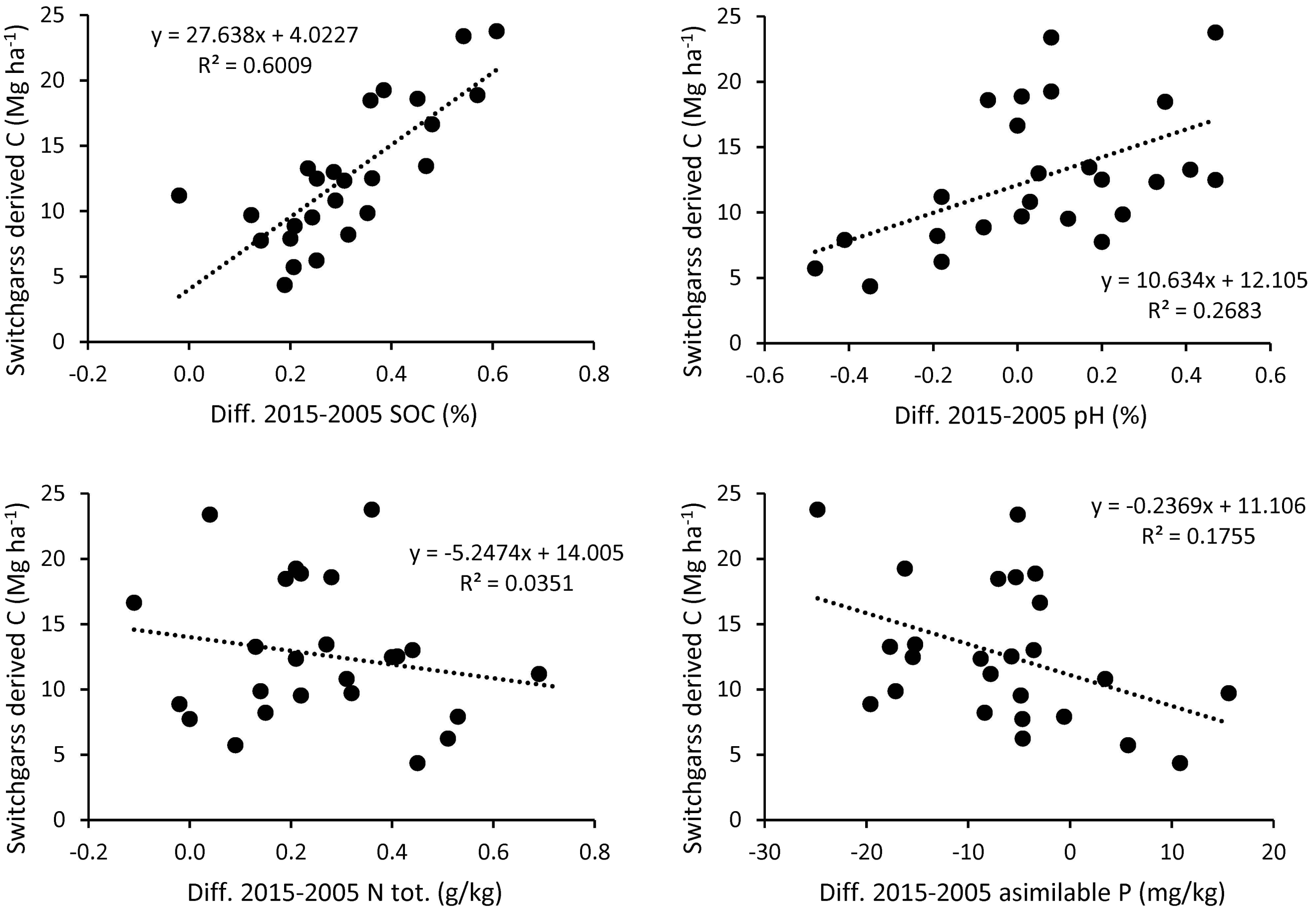

FIGURE 2 Relationships between the C derived from switchgrass and the SOC, nitrogen, phosphorus, and pH changes with time (2005–2015). The number of available C-derived samples was 25

aeration of marginal or degraded soils. Such slow SOC increase with time is in the range of other few long-term studies on different perennial crops (Frank et al., 2004; Garten & Wullschleger, 2000; Ma et al., 2000; Monti et al., 2012; Zan et al., 2001). However, these slow but gradual changes are usually obscured by the variable background levels of C already present in the soil depending on the type and degree of marginality (Lockwell et al., 2012; Monti & Zegada-Lizarazu, 2016). Therefore, long-term data, as in the present study, are needed to reduce the uncertainties in forecasting the SOC accumulation potential of perennial crops such as switchgrass in marginal lands.

The inferred SOC accumulated by switchgrass, however, cannot be solely imputable to root biomass and distribution, as rhizomes (an important belowground plant

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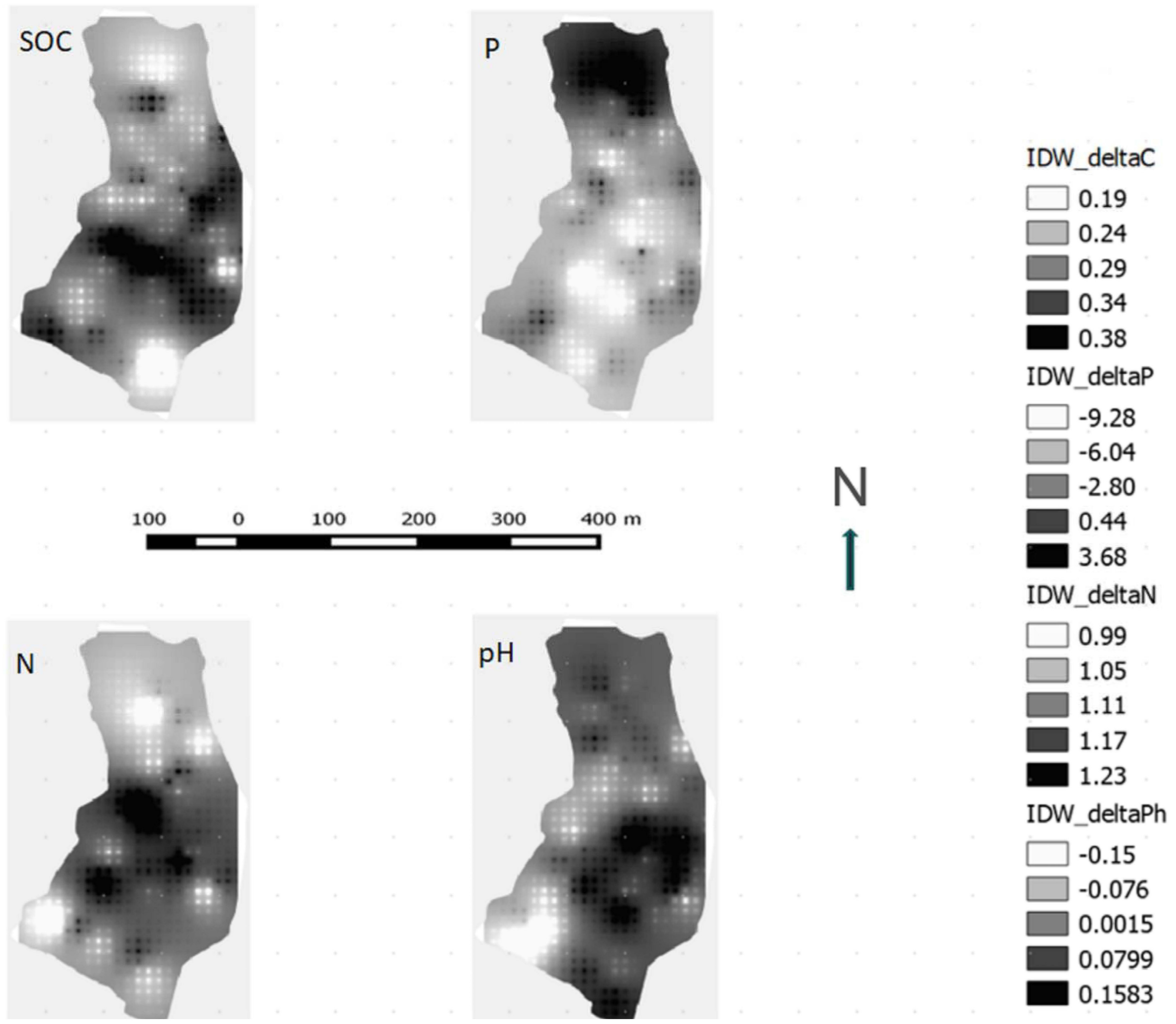

FIGURE 3 Thematic maps of soil organic carbon (SOC; $g\,kg^{-1}$), nitrogen (N; $g\,kg^{-1}$), phosphorus (P; $mg\,kg^{-1}$), and pH changes during the 2005–2015 period (delta of inverse distance weighted [IDW] interpolation method). Maps show the patchy variations along the field for each parameter

component) also played a significant role. Rhizomes represent close to 60% of the total belowground biomass (Frank et al., 2004) of perennial crops. In the case of switchgrass, Garten et al. (2010) indicated that the C stored in the rhizomes represented only 20% of the total stored in the belowground biomass, probably because most of the C is allocated to the root fraction, differently than in other perennial grasses (Agostini et al., 2015; Ferchaud et al., 2016). In any case, rhizomes may constitute an important fraction of the total SOC accumulated in the 13-year period of the present study, but still more information is needed to understand better the turnover of rhizomes, and their dynamics and longevity. In fact, their carbohydrate and crude protein contents vary largely even within a growing season making difficult the estimation of the real contribution of rhizomes to the total SOC accumulated in more than a decade. Another factor influencing SOC could be the litter accumulation and decomposition rate, although very variable in function of the prevailing seasonal meteorological conditions and the agronomic management characteristics of the site. In the present study, the no-tillage condition may have allowed the accumulation of relevant litter quantities along the years. On the contrary, in short-term studies, the litter accumulation was rather variable: Frank et al. (2004) reported little litter biomass (4%–5%), while Anderson-Teixeira et al. (2013) reported relatively large quantities of litter C inputs (100–400 $g\,C\,m^{-2}$) to the system by switchgrass. In the present study, however, the specific long-term contribution to the SOC of litter cannot be determined. Besides that, the root tissue and litter chemistry can also affect the SOC accumulation. Garten et al. (2011) showed that an increase in the C:N ratio (e.g., by N fertilization) changes the root tissue and litter chemistry, implying that N fertilization could increase C:N ratio, and therefore may accelerate root decomposition affecting SOC accumulation. In our case, the plots were not regularly fertilized, so the changes on litter and root tissue chemistry may be limited. In fact, there are some studies that indicate a reduction of residue decomposability due to N deficiency (Henriksen & Breland, 1999). Moreover, recent evidence indicates that the lower mineralization rate of switchgrass roots may be due a specific highly recalcitrant C pool and to a reduced accessibility to decomposers (Ferrarini et al., 2021, 2022).

The increased SOC along the field, however, was very patchy, with the highest increments registered in the center portion of the field and the lowest in the top and bottom extremes of the hill (Figure 3) probably in relation to the reported heterogeneous characteristics of the soil in terms of structure, mineral content, and slope (Di Virgilio et al., 2007). Soil N stocks also increased along with the soil C sequestration, although no direct relationship with the C derived from switchgrass was found (Figure 2). The overall difference between 2005 (3-year-old plants) and 2015 (13-year-old plants) was 0.24 g N kg^{-1} (Table 2). In this case, the increments along the whole field were also highly variable, but somehow reflecting the patchy distribution of SOC increments. The increments in N stocks (Figure 3) could be related to the efficient annual recycle of N between the canopy and the belowground biomass throughout the lifetime of the plant (Zegada-Lizarazu et al., 2012). It is known that increased SOC affects mostly the N cycling and to a lesser degree the soil physical properties. Thus, organic N release could be considered an effect of increased SOC (Palmer et al., 2017). Besides that, the increased N stocks could be due in part to atmospheric N deposition, the presence of indigenous N-fixing bacteria in the soil, accumulated litter, root exudates, fast root turnover, and microbial necromass incorporated into the soil organic matter pool (Li et al., 2018, 2020; Monti et al., 2019). More importantly is, however, the high variability in the soil characteristics, which varied consistently within short distances, and this had a direct effect on above- and belowground biomass productivity (Di Virgilio et al., 2007). In this study (which is a follow-up study to that of Di Virgilio et al., 2007), no statistically significant relationships between SOC increments and soil texture were found, nor with mineral (N, P) contents (data not shown). Such variability, however, indicates that the increased SOC in a long-term plantation may depend on many undetermined factors related to the crop and specific pedoclimatic conditions. Moreover, mechanistic explanations for the variable SOC and N increments cannot be given based on the limited dataset available in the present study associated with the high costs of long-term studies and the high number of soil samples that were taken in an attempt to characterize the spatial variability across the field. In a 3-year study, Li et al. (2020) indicated that low to high N fertilization reduced the SOC variability at plot-level scale. On the contrary, the present trial was carried out with minimum inputs in terms of fertilization, tillage, irrigation, etc., which may add up to the prevalent indigenous heterogeneity of the soil. It is however difficult to estimate if the former soil use may have smoothed or added to the SOC variability in the long term. Modeling SOC and N variation studies along different sites indicated that their variability was in part due to climatic conditions (with temperature playing a central role) and to a lesser extent to soil heterogeneity and former land uses (Ledo et al., 2020; Martinez-Feria & Basso, 2020; Nocentini et al., 2015).

As for the extractable P, an inverse trend to SOC and N contents (Table 2) was evident. The extractable P decreased from about 24 mg kg^{-1} (2005) to 19 mg kg^{-1} (2016) and a close negative relationship was also found between P and C derived from switchgrass ($r = -0.42^*$; Figure 2). Moreover, the decrease was surveyed in almost all the field, except for the very extreme part at the top of the hill where a small increase was noticed (Figure 3). The decrease in extractable P could be mainly related to uptake by the extended root system and export into the harvested biomass, indicating that some degree of maintenance fertilization in the long term may be necessary to compensate those losses.

All over the field, a slightly higher pH was registered in 2015 compared with 2005 (Table 2), such difference, however, was not statistically significant. Moreover, the pH increases were more remarkable in the center of the field, somehow reflecting the patchy increases in SOC (Figure 3). However, it is worth noting that all over the field the soil remained moderately alkaline (pH ≈ 7.9), in line with the soil capacity to maintain exchangeable cations and close to the ideal range for optimum soil productivity and plant growth. In a greenhouse study, Zhang et al. (2015) demonstrated that switchgrass maximized its fresh biomass production in a pH range of 6.3–8.1, while Hanson and Johnson (2005) indicated that the best soil pH for stand establishment was between 5 and 8. Therefore, these results suggest that meaningful soil fertility enhancements in the long term would not be significantly affected.

5 | CONCLUSIONS

It was evidenced that a long-term switchgrass plantation had positive effects on C storage in a marginal land. A significant positive correlation was observed between the C derived from switchgrass and the SOC gain over a 13-year period. The increased SOC along the field, however, was irregular, probably in relation to the heterogeneous characteristics of the soil in terms of structure and

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mineral content. Soil N stocks have also increased irregularly. Such results, besides suggesting that switchgrass grown in marginal land could be a sustainable strategy to contribute to climate change mitigation, indicate the long-term potential of the crop to increase the SOC and N in function of not only the crop age, site-specific management, and climatic conditions, but also on the soil characteristics and related beneficial effects (i.e., fertility, water holding capacity, ecosystem services, etc.). The present study laid the basis for a more comprehensive understanding of the real and tangible effects of perennial energy crops in enhancing soil health, particularly when grown in marginal land while providing a net soil C sequestration potential and reducing the risk of land abandonment. In summary, this study provides spatially explicit quantification of soil quality changes and soil C sequestration at field level, suggesting that switchgrass could be used to revitalize marginal lands in a sustainable and productive manner.

ACKNOWLEDGMENTS

This work was partially carried out in the framework of the OPTIMA project (GA 289642) and prosecuted in the framework of the MAGIC project (GA 727698). The authors acknowledge Alessandro Zatta, Giuseppe Pritoni, Giuseppe Di Girolamo, and Angela Vecchi for the technical supervision of the trails, and Paola Gioacchini for running the carbon isotope discrimination analyses on the collected soil samples.

CONFLICT OF INTEREST

The authors declare that they do not have competing financial interests or personal relationships that could influence the present work.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available at Zenodo at https://doi.org/10.5281/zenodo.6365668.

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How to cite this article: Zegada-Lizarazu, W., Zanetti, F., Di Virgilio, N. & Monti, A. (2022). Is switchgrass good for carbon savings? Long-term results in marginal land. *GCB Bioenergy*, *14*, 814–823. https://doi.org/10.1111/gcbb.12944

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