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ORIGINAL RESEARCH

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Biofuel production and soil GHG emissions after land-use change to switchgrass and giant reed in the U.S. Southeast

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Abstract

United States mandated the production of biofuel from lignocellulosic feedstocks. Nonetheless, the cultivation of these feedstocks may produce debates, as agricultural land is scarce and it is primarily needed for food production and grazing. Thus, it is thought that biofuel production should be placed on land with low economical value (i.e., marginal land). At the same time, depending on what land is considered marginal and therefore available for lignocellulosic crops, different greenhouse gas impacts will be generated upon land use change. Here, we attempted to estimate the biomass production and soil greenhouse gas emissions of the cultivation of switchgrass (*Panicum virgatum* L.) and giant reed (*Arundo donax* L.) in the U.S. Southeast, when converting distinct former land uses. We employed the NLCD and the SSURGO databases to select grasslands, shrublands, and marginal croplands and to then allocate switchgrass and giant reed on this land basing on biophysical parameters included in the Land Capability Classification. After calibration, the DAYCENT model was employed to simulate 15-year cultivation of both crops in the U.S. Southeast. Florida, Georgia, Mississippi and South Carolina were the States with the highest availability of land, thus the highest potential for biofuel production. Among scenarios, the one converting poor grazing land and marginal croplands yielded the greatest benefits: converting 3.6 Mha of land, 44 Mt/year of dry biomass could be produced, storing 0.05 Mt/year of soil organic C at the same time. In this scenario, considering 80-km supply areas, nineteen biorefineries could deliver 7,124 Ml/year of advanced ethanol across the region. When minimizing giant reed invasion risks through reallocating giant reed outside flooded areas, 4,695 Ml/year of advanced ethanol could be still delivered from thirteen biorefineries, but the scenario turned in a biogenic greenhouse gas source (3.2 Mt CO_2eq/year).

KEYWORDS

biofuel, DAYCENT, giant reed, greenhouse gas, land use change, switchgrass

1 | INTRODUCTION

In order to achieve energy security (uninterrupted availability of energy sources at an affordable price) and a reduction in greenhouse gases (GHG) emissions (sustainability), policies have been promulgated in the United States for the production of bioenergy from lignocellulosic feedstocks, including the Renewable Fuel Standard

(RFS2; The Energy Independence and Security Act, 110th Congress of the United States, 2007). Recently, Bacovsky, Ludwiczek, Ognissanto, and Worgetten (2013) found a total of 14 cellulosic biorefineries existing or under construction in the United States, with a total planned fuel production capacity of 0.33 Mt/year (i.e., 418 Ml/year). While this represents a large test of this new technology, the scale of this production still pales compared to the levels mandated in RFS2 or that of the existing conventional corn ethanol industry (EIA 2017; Peplow, 2014). Despite a more difficult transformation process required compared to first-generation biofuels (e.g., corn ethanol), the main advantages of lignocellulosic crops (e.g., switchgrass) used to produce advanced ethanol are the lower environmental impacts during cultivation (Adler, Del Grosso, & Parton, 2007; Fazio & Monti, 2011), the possibility to reduce biogenic GHG emissions through soil organic carbon (SOC) storage (Agostini, Gregory, & Richter, 2015) and the opportunity to avoid competition for land, since they can satisfactorily grow also in marginal situations (Quinn et al., 2015) that would not be suited for the cultivation of conventional food crops. The conversion to biofuels of land with high amounts of C (e.g., forests) should be avoided in order to not generate a large C debt (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008) from land use change (LUC; i.e., loss of aboveground biomass C and soil organic C upon conversion). While conversion of existing croplands to biofuel feedstock crops will often increase SOC in those systems (Davis et al., 2012; Qin, Dunn, Kwon, Mueller, & Wander, 2016), the displacement of existing crop production can lead to an indirect land use change (ILUC) effect due to the conversion of more land somewhere else (this land could be rich in C and its conversion impactful) as an answer to increased prices (Searchinger et al., 2008). Land allocation of lignocellulosic feedstocks is therefore essential for sustainable agriculture: to present, it is widely thought that lignocellulosic crops should be best allocated on marginal land (Fargione et al., 2008; Gelfand et al., 2013; Quinn et al., 2015). Defining marginal land is still challenging but, in general, it can be identified as land with a low economical value ("economical" embeds the productive, environmental, and social values; Kang et al., 2013; Richards, Stoof, Cary, & Woodbury, 2014). Grasslands and shrublands, especially if characterized by pedo-climatic limitations (poor), are considered marginal land. Although grasslands and shrublands are natural ecosystems, they do not store as much C as forests (Fargione et al., 2008), and their conversion could generate a C debt promptly repayable by the high C deposition rates from the lignocellulosic perennial vegetation (Agostini et al., 2015). On the other hand, marginal croplands (low productivity land) could be converted. This conversion might generate ILUC effects, however, low, thanks to a possible intensification of food production in nonmarginal croplands (Heaton et al., 2013; Matson, Parton, Power, & Swift, 1997). So, converting biophysically poor grasslands and shrublands will minimize ILUC impacts by only displacing a small part of the grazing livestock, but will give more uncertain benefits in terms of GHG emissions because of less predictable SOC trends (Qin et al., 2016) and because of an increase in management-related emissions, including direct and indirect nitrous oxide (N_2O) emissions from the use of N fertilizers (Del Grosso et al., 2006; Erisman, van Grinsven, Leip, Mosier, & Bleeker, 2010). On the contrary, converting marginal croplands may generate ILUC effects, but will likely generate great GHG benefits through SOC deposition (Qin et al., 2016).

Cai, Zhang, and Wang (2011) performed an analysis to estimate the global potential to produce biofuels from marginal land and found out that the United States, depending on the scenario considered, may have 43–127 Mha of available marginal land (i.e., abandoned land, wasteland, degraded land), mostly in the eastern part of the country. The U.S. Southeast may thus have a high potential for the cultivation of lignocellulosic feedstocks for advanced ethanol. Currently, bioethanol production plants are scarce in the region: only the 2.5% of U.S. bioethanol was produced in the Southeast in the year 2016, whereas most of it (91%) was produced in the Corn Belt region (EIA, 2017). Nonetheless, the climate in the U.S. Southeast seems ideal for yielding the high biomass supplies required by the bioenergy industry, with moderate temperature regimes (9.2–25.4°C, as yearly mean) and ample precipitation (400–1,600 mm/year) (Mesinger, DiMego, & Kalnay, 2006).

Both switchgrass (*Panicum virgatum* L.) lowland cultivars and giant reed (*Arundo donax* L.), find ideal conditions for growth in warm climates with sufficient water availability (Alexopoulou et al., 2015; Lewandowski, Scurlock, Lindvall, & Christou, 2003) and are tolerant of several pedo-climatic limitations such as high temperatures, drought, or salinity (Quinn et al., 2015), and thus may be appropriate for cultivation on marginal land in the U.S. Southeast. Switchgrass is a U.S. indigenous grass at the center of national projects for the production of bioenergy (McLaughlin & Kszos, 2005; Wright & Turhollow, 2010). Giant reed has a great potential for bioenergy production (Lewandowski et al., 2003), as it is able to even reach yields over 40 Mg/ha of dry biomass in the proper environment (Hidalgo & Fernandez, 2000). As a bioenergy feedstock, giant reed has been mainly investigated in the Mediterranean Europe (Alexopoulou et al., 2015; Angelini, Ceccarini, & Bonari, 2005; Cosentino, Scordia, Sanzone, Testa, & Copani, 2014; Hidalgo & Fernandez, 2000; Monti & Zegada-Lizarazu, 2015), and not as much in the United States, due to concerns about it being an invasive species (Ceotto & Di Candilo, 2010; Herrera & Dudley, 2003), especially in certain areas (e.g., California). Nonetheless, invasion risks can be minimized by properly allocating and managing giant reed (Ceotto & Di Candilo, 2010).

Besides switchgrass and giant reed, another valuable candidate for producing biofuel in the United States would be miscanthus (*Miscanthus x giganteus* Greef et Deuter); it has in fact been already utilized in several simulation studies together with switchgrass (Davis et al., 2012; Hudiburg et al., 2016; Qin, Zhuang, & Cai, 2015). But, since giant reed is more heat tolerant than miscanthus (Quinn et al., 2015), the former was considered more suited to the U.S. Southeast where mean yearly temperatures can reach up to 25.4°C (Mesinger et al., 2006) and was employed for the present analysis; no surprise that, when compared side-by-side in a long-term experiment in the Mediterranean, giant reed showed higher (+18%) yields than miscanthus (Alexopoulou et al., 2015). Furthermore, there are evidences that switchgrass and giant reed can, in certain conditions, be more effective in storing SOC compared to miscanthus: in fact, they can potentially sequester C into the deeper soil layers (Qin et al., 2016), probably thanks to their evenly distributed roots down to 200 cm (Monti & Zatta, 2009). In a recent review study, Ge, Xu, Vasco-Correa, and Li (2016) found that giant reed can adapt to a broader range of environmental conditions than miscanthus and that it can achieve higher biomass yields and comparable bioethanol yields. It is thus strongly believed that giant reed's potential deployment as a bioenergy crop deserves more research than it has been carried out up to present.

It is, however, unclear whether switchgrass or giant reed would be a more appropriate bioenergy feedstock in the U.S. Southeast. Despite its high potential (Monti, Barbanti, Zatta, & Zegada-Lizarazu, 2012), switchgrass does not typically reach the yields and SOC storage rates achieved by giant reed (Alexopoulou et al., 2015; Hidalgo & Fernandez, 2000; Monti & Zegada-Lizarazu, 2015; Nocentini & Monti, 2017). Only a few direct comparisons of switchgrass and giant reed are currently present in the literature (Monti & Zatta, 2009; Kering, Butler, Biermacher, & Guretzky, 2012; Alexopoulou et al., 2015; Nocentini & Monti, 2017), but, until now, giant reed was always reported to show higher yields (Alexopoulou et al., 2015; Kering et al., 2012), higher root biomass (Monti & Zatta, 2009), or higher SOC accumulation rates (Nocentini & Monti, 2017). Kering et al.(2012) reported that in the United States giant reed yielded 58% greater biomass than switchgrass after both crops were fully established, and Alexopoulou et al. (2015) observed 56% greater mean biomass yield in giant reed than in switchgrass during 10years of side-by-side cultivation in Northern Italy. Monti and Zatta (2009), at the sixth year of cultivation of both perennial crops, found that giant reed had 61% greater root biomass, whereas Nocentini and Monti (2017) measured 111% greater SOC storage in giant reed than in switchgrass after 10 years of cultivation, pointing out that organic inputs to the soil derived from giant reed harvest residues were also greater. Giant reed thus seems to have a higher potential to displace fossil fuels and to increase soil C stocks. However, switchgrass may be more attractive to farmers for the following reasons: the availability of the genetic material in the United States, social acceptance (giant reed is thought to be invasive and is anyway less known than switchgrass, which in the Unites States is the selected model bioenergy crop; Wright & Turhollow, 2010) and production costs. If costs for land rent, soil tillage, fertilizer application, and weeding were assumed equal for the two crops, annualized costs per unit of land basis to produce giant reed would still be almost two times higher (Perrin, Vogel, Schmer, & Mitchell, 2008; Soldatos, Lychnaras, Asimakis, & Christou, 2004), without taking into account the probable investments in new farm machineries needed to harvest giant reed. Therefore, although giant reed is expected to yield much more biomass than switchgrass in the U.S. Southeast, it still would be less profitable when also considering the year by year yields fluctuations. Nonetheless, it is widely thought that more expensive, but higher yielding biomass crops such as miscanthus (Soldatos et al., 2004) can positively impact the U.S. biofuel industry, GHG balance, and economy (Davis et al., 2012; Hudiburg et al., 2016; Qin et al., 2015). Thus, we propose that a mix of more biofuel crops, with different characteristics would be eventually beneficial, taking into account other factors as biodiversity sheltering and the production risks linked to monocultures. More crops with distinct characteristics would also better fit within a landscape with variable parameters (Heaton et al., 2013). Moreover, the use of a higher yielding crop together with switchgrass, such as giant reed, will reduce the land requirements for biofuel production and will allow production within a smaller radius around the biorefineries, mitigating at the same time the impact of transportation.

In this study, we employed the biogeochemical process model DAYCENT (Parton, Hartman, Ojima, & Schimel, 1998) to simulate the cultivation of switchgrass and giant reed in the U.S. Southeast to support the production of advanced bioethanol. The DAYCENT model simulates cycling of C, N, and water in natural and agricultural systems based on biophysical factors, current and historical land use, vegetation cover, and management practices (Del Grosso et al., 2011; Parton et al., 1998). While switchgrass has been extensively experimented in other U.S. simulation studies (Davis et al., 2012; Field, Marx, Easter, Adler, & Paustian, 2016; Hudiburg et al., 2016; Qin et al., 2015), to our knowledge, this is the first regional scale simulation involving giant reed as a biofuel crop. The DAYCENT model has already been proven capable to simulate perennial energy crops yields, SOC and N_2O emissions in previous studies (Davis et al., 2012; Field et al., 2016; Hudiburg et al., 2016). We simulated feedstock production on marginal croplands, and both biophysically poor and biophysically good grazing land (grasslands and shrublands), in order to analyze possible trade-offs between different land use change options. The simulation outputs allowed the estimation of dry biomass yields, SOC stocks changes and total soil N_2O emissions. We then used model outputs within a Geographic Information System (GIS) environment to predict the best position of future potential bioethanol plants by biomass availability.

2 | METHODS

2.1 | Calibration-evaluation process

Calibration of the DAYCENT model for switchgrass (lowland ecotype) has already been achieved and has been evaluated for both Unites States and Europe environments in our previous work (Field et al., 2016; Nocentini, Di Virgilio, & Monti, 2015). To obtain the parameterization of the model for giant reed, besides using field data from our own long-term experiments in North Italy (Alexopoulou et al., 2015; Monti & Zegada-Lizarazu, 2015), a literature research has been carried out to select those studies which reported significant information on giant reed's aboveground and below-ground C pools. Since the aim of this study was a simulation at the regional scale, characterized by gradients in climate and soil types, data recorded in a variety of pedo-climatic conditions were used for the calibration-evaluation process (Table 1). Long-term studies (showing changes in above- and below-ground biomass over time), studies from sites with different climatic conditions (to understand the growth of the crop as related to temperature and precipitation amount and distribution) and studies where fertilization and irrigation levels varied (analyzing the response of the crop to nutrient and water inputs) were included in the calibration dataset. For the evaluation dataset, studies with marked longitudinal and latitudinal differences (South Italy, North Italy, Spain, Germany, Texas, Oklahoma) were selected, as well as studies with varying agronomic inputs (nitrogen and irrigation levels). Unpublished data on aboveground yields from the long-term trial described by Cattaneo, Barbanti, Gioacchini, Ciavatta, and Marzadori (2014) were also used during calibration.

A recently improved version of DAYCENT was employed for this study (Zhang, 2016), in which, among other

TABLE 1 List of literature studies used during DAYCENT calibration and evaluation for giant reed

Reference	Place	Years	Data type	Data points	Use
Alexopoulou et al. (2015)	North and South Italy	2004–2015	Yield	3	Calibration
Angelini et al. (2005)[a]	Central Italy	1996–2001	Yield	4	Evaluation
Bacher, Sauerbeck, Mix-Wagner, and El Bassam (2001)	Germany	1997–2001	Yield	1	Evaluation
Cattaneo et al. (2014)	North Italy	2002–2011	SOC	1	Calibration
Ceotto and Di Candilo (2011)	North Italy	2002–2009	SOC	2	Evaluation
Cosentino et al. (2014)[a,b]	South Italy	1998–2001	Yield	19	Calibration
Di Candilo, Ceotto, Librenti, and Faeti (2010)[a]	North Italy	2007–2009	Yield	5	Evaluation
Fagnano, Impagliazzo, Mori, and Fiorentino (2015)[a]	South Italy	2004–2012	Yield; SOC	4; 1	Evaluation
Hidalgo and Fernandez (2000)	Spain	1997–1999	Yield	2	Evaluation
Kering et al. (2012)[a]	Oklahoma	2008–2010	Yield	1	Evaluation
Mantineo, D'Agosta, Copani, Patané, and Cosentino (2009)[a,b]	South Italy	2002–2006	Yield	2	Evaluation
Monti and Zatta (2009)	North Italy	2002–2007	Root biomass	1	Calibration
Monti and Zegada-Lizarazu (2015)[a]	North Italy	1997–2014	Yield; SOC	6; 2	Calibration
Nassi o Di Nasso et al. (2013)	Central Italy	2009–2011	Yield; Root biomass	1; 1	Calibration
Nocentini and Monti (2017)	North Italy	2004–2014	SOC	1	Calibration
Sarkhot, Grunwald, Ge, and Morgan (2012)	Texas	1970–2008	SOC	1	Evaluation
Unpublished[c]	North Italy	2002–2016	Yield	6	Calibration

[a]Different N treatments.
[b]Different irrigation levels.
[c]Unpublished yields from the experiment described in Cattaneo et al. (2014).

parameters, *Kcet*, the crop coefficient (Kc) for evapotranspiration, has been implemented, allowing to more accurately simulate crop water use and phenology. Therefore, new adjustments to switchgrass parameterization for lowland cultivars were also made in parallel with the calibration of the parameters for giant reed (Table 2). We decided to simulate only switchgrass lowland cultivars because they are more likely to be adopted by farmers for their higher yields at the lower latitudes of the U.S. Southeast. As previously for switchgrass (Nocentini et al., 2015), giant reed growth was divided in phases, since a decline in yields in time has been observed in our field experiments (Monti & Zegada-Lizarazu, 2015), and in the literature (Angelini, Ceccarini, Nassi o Di Nasso, & Bonari, 2009), both showing the decline to occur after the eighth year after establishment. Several papers also show how giant reed reaches its maximum yielding capacity in the third year (Alexopoulou et al., 2015; Hidalgo & Fernandez, 2000; Monti & Zegada-Lizarazu, 2015; Nassi o Di Nasso, Roncucci, & Bonari, 2013). Thus, giant reed growth phases were defined as: (i) "establishment" (years 1–2), (ii) "maximum yielding phase" (years 3–8), (iii) "mature phase" (years 9–15). Expert judgment was used to identify individual

TABLE 2 List of the main DAYCENT parameters involved in switchgrass (SG) and giant reed (GR) parameterization and their respective values

Parameter	Description	SG value	GR value
prdx[a]	Coefficient to calculate aboveground production as a function of solar radiation	0.250	0.280
ppdf (1)	Optimum temperature for production (°C)	30	30
ppdf (2)	Max. temperature for production (°C)	44	45
ppdf (3)	Left curve shape of the function of temperature effect on growth	0.75	0.35
ppdf (4)	Right curve shape of the function of temperature effect on growth	2	3.8
pltmrf[a]	Planting month reduction factor to limit seedling growth	0.4	0.4
fulcan	Value of *aglivc* (aboveground live C) at full canopy cover	700	900
kcet	Crop coefficient used to calculate evapotranspiration	0.54	0.60
cfrtcn (1)	Maximum fraction of C allocated to roots under max. nutrient stress	0.70	0.83
cfrtcn (2)[a]	Minimum fraction of C allocated to roots with no nutrient stress	0.36	0.28
cfrtcw (1)	Maximum fraction of C allocated to roots under max. water stress	0.80	0.73
cfrtcw (2)[a]	Minimum fraction of C allocated to roots with no water stress	0.36	0.28
claypg	Number of soil layers to determine water and mineral N available for crop growth	9	9
biomax	biomass level above which the minimum and maximum C/E ratios of the new shoot increments equal pramn(*,2) and pramx(*,2), respectively, (g biomass/m^2)	200	100
pramn (1, 1)	Minimum C/N ratio with zero biomass	37	47
pramn (1, 2)	Minimum C/N ratio with biomass greater than or equal to *biomax*	57	67
crprtf (1)	Fraction of N transferred to a vegetation storage pool from grass/crop leaves at death	0.6	0.73
snfxmx (1)	Symbiotic N fixation maximum for grassland/crop	0.002	0.008
fligni (1, 1)	Intercept for equation to predict lignin content fraction based on annual rainfall for aboveground material	0.02	0.04
fligni (1, 2)	Intercept for equation to predict lignin content fraction based on annual rainfall for juvenile live fine root material	0.06	0.08
fligni (1, 3)	Intercept for equation to predict lignin content fraction based on annual rainfall for mature live fine root material	0.13	0.15
mrtfrac	Fraction of fine root production that goes to mature roots	0.4	0.4
cmxturn	Maximum turnover rate per month of juvenile fine roots to mature fine roots	0.5	0.3
rdrj	Maximum juvenile fine root death rate	0.95	0.90
rdrm	Maximum mature fine root death rate	0.80	0.45
rdsrfc	Fraction of the fine roots that is transferred into the surface litter layer	0.2	0.2
cmix	Rate of mixing of surface SOM and soil SOM	0.5	0.5
npp2cs (1)	GPP as a function of NPP to determine C stored in the carbohydrate pool	2.0	2.0
fallrt	Fall rate of standing dead biomass	0.1	0.1

[a]Values for the "maximum yielding phase".

growth model parameters in need of adjustment to better represent giant reed growth patterns, then parameter values were adjusted by hand (Table 2) to best match empirical data on harvested biomass yields, root biomass, and SOC changes as summarized in Table 1. To simulate establishment, the *pltmrf* parameter was set lower (0.1) in order to reproduce limited growth of the new seedlings and more C was allocated to roots through the *cfrtcn (2)* and *cfrtcw (2)* parameters (0.50). Root:shoot ratio of giant reed was shown to be ~2 at the end of the first year and ~0.6 in the following years (Nassi o Di Nasso et al., 2013). To simulate the mature phase, the *prdx* value was set lower (0.225) to reduce the yield capacity of giant reed. The *sfnxmx (1)* parameter was set slightly higher than 0 (Field et al., 2016), only to simulate switchgrass and giant reed capacity to achieve considerable yields without N fertilization (Alexopoulou et al., 2015; Monti & Zegada-Lizarazu, 2015).

The DAYCENT model was able to simulate giant reed yields ($r = .68^{**}$; Figure 1), root biomass and SOC ($y = 1.326x$, $r = .79^{*}$) with good accuracy. Unfortunately, very few studies reported the root biomass of giant reed, which, however, seems to reach values significantly over 10 Mg/ha, both in fine- (Monti & Zatta, 2009) and sandy-textured soils (Nassi o Di Nasso et al., 2013), once the crop is established. While switchgrass model calibration was evaluated for soil N_2O emissions (Field et al., 2016; $r = .54$), no data are currently present in the literature about soil N_2O emissions in giant reed. Nevertheless, biomass N content was considered during model parameterization (Kering et al., 2012; Nassi o Di Nasso et al., 2013), which helped to deliver more reliable model outcomes on N_2O emissions.

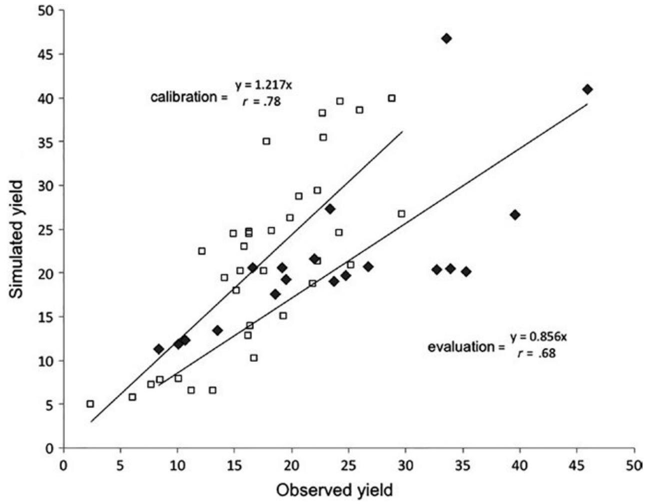

FIGURE 1 Observed versus simulated giant reed yields (Mg ha^{-1} $year^{-1}$) used for calibration and evaluation; all points aggregated show $r = 0.64^{***}$, root mean square error *RMSE* = 9.2 Mg/ha (calibration points = white square, evaluation points = black diamond)

2.2 | Land selection and crop allocation

The study was conducted in the U.S. Southeast and the following States were included: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, and Virginia. One of the goals of this study was to assess trade-offs among distinct land use change (LUC) options for the cultivation of perennial biofuel crops in the U.S. Southeast. Three LUC strategies were simulated: conversion of (i) grasslands and shrublands with considerable biophysical marginal traits, (ii) grasslands and shrublands without major biophysical constraints for agriculture, and (iii) croplands with considerable biophysical marginal traits. So, our criterion of marginal land identification was one using “land use + land quality”, similar to another recent U.S. study (Emery, Mueller, Qin, & Dunn, 2017). In order to identify land with the above written characteristics, two databases were principally used: the National Land Cover Database (NLCD) 2006 (Wickham et al., 2013) and the Land Capability Classification which is included in the SSURGO database (Ernstrom & Lytle, 1993). NLCD's selected classes were: areas dominated by shrubs less than 5 m tall, with shrub canopy typically greater than 20% of the total vegetation (code 52); areas dominated by herbaceous vegetation, which is generally greater than 80% of total vegetation (71); and areas being actively tilled and used for the production of annual crops and also perennial woody crops (82). The Land Capability Classification uses eight classes, from I to VIII, to express growing limitation of a certain land for agricultural use: a land in class I has no limitations for agricultural use, whereas, on the opposite, a land in class VIII has severe limitations that avoid any type of agricultural use. We estimated that land in classes from I to VI were suitable for the cultivation of switchgrass and giant reed. Although land in classes V and VI can already have some serious limitations, we considered that the low management required by the two perennial crops (Lewandowski et al., 2003) and their suitability for marginal land (Quinn et al., 2015) would still render their cultivation feasible and economically sustainable; for example, in their analysis, Gelfand et al. (2013) successfully converted to biofuel land in capability class VII. Five scenarios were eventually simulated (Table 3): 1A) conversion of grasslands and shrublands in capability classes between IV and VI (poor grazing land); 2A) conversion of 50% of grasslands and shrublands in capability classes between I and III (good grazing land); 1B) conversion of grasslands and shrublands in capability classes between IV and VI plus conversion of croplands in capability classes V and VI (poor grazing land + marginal croplands); 2B) conversion of 50% of grasslands and shrublands in capability classes between I and III plus conversion of croplands in capability classes V and VI (good grazing land + marginal croplands); B) only conversion of croplands in capability classes V and VI (marginal croplands). We decided to convert only 50% of

TABLE 3 Bioenergy land conversion scenarios, based on current land use (NLCD) and Land Capability Classification (LCC) ratings

Scenario name	Good grazing land (50% of LCC I–III)	Poor grazing land (LCC IV–VI)	Marginal crop-lands (LCC V–VI)
1A		X	
2A	X		
1B		X	X
2B	X		X
B			X

grasslands and shrublands in capability classes between I and III to avoid possible significant ILUC effects given by the displacement of livestock grazing that occurs in part on this land (U.S. Department of Agriculture 1997); moreover, the total surface occupied by this land use in the U.S. Southeast is large (4.7 Mha), thus, maintaining half of it to livestock grazing, allowed us to deliver more plausible outcomes at the regional scale. Although croplands in capability classes V and VI occupy a small fraction of the tilled surface in the Southeast (4.9%), their conversion could still generate ILUC effects. We, however, considered these effects avoidable by intensifying food production in nonmarginal croplands (Heaton et al., 2013; Matson et al., 1997).

Federally owned land was identified using the USGS Federal Lands of the United States data layer (U.S. Geological Survey 2015) and excluded from the study because not likely to be converted. Also areas with slope >15% were excluded because considered not suitable for cropping. After filtering for federally owned and high slope land, the simulation area was reduced by 10.9%.

In this study, differently from previous U.S. regional simulations that modeled biofuel crops cultivation (Davis et al., 2012; Hudiburg et al., 2016; Qin et al., 2015), switchgrass and giant reed were not cultivated on all the selected land, but were spatially allocated following two different criteria. The first was a criterion of "spatial intensification," as described by Heaton et al. (2013): basing on some of the characteristic of the two crops, we tried to identify those marginal traits of the land that could be best overcome by either switchgrass or giant reed. In order to do that, we used the following Land Capability Classification subclasses, which attribute the specific major limitation of a certain land ranked from II to VIII: subclass "e" is for soils where the susceptibility to erosion is the dominant problem or hazard in their use, "w" is for soils where excess water is the dominant hazard, "s" is for soils that have limitations within the rooting zone (i.e., shallowness, stones, low moisture-holding capacity, low fertility, salinity), and "c" is for soils where there are climatic limitations (temperature or lack of moisture). Switchgrass was allocated on land ranked "e" because of the lower soil disruption that is brought with seeding at establishment compared to the implant of rhizomes required by giant reed and for its higher tillering that covers the soil more completely (direct observation), resulting in lower erosion risks. Giant reed was allocated on land ranked "w" because it is also a riparian species that survives and performs well in flooded conditions (Herrera & Dudley, 2003; Quinn et al., 2015).

Both, switchgrass and giant reed, have deep and dense root systems (Monti & Zatta, 2009) that can allow them to overcome rooting zone limitations. Furthermore, switchgrass can better grow in drier soils, whereas giant reed reacts better in saline soils (Quinn et al., 2015), while both can achieve high yields despite the lack of soil nitrogen (Lewandowski et al., 2003). Thus, it was not possible to allocate either one of the two crops following the "spatial intensification criteria" on land ranked "s." On the land belonging to this subclass we therefore decided to allocate switchgrass, applying what we called an "economical/consensus" criterion. In fact, as pointed out in the introduction, the availability of the genetic material, social acceptance and the lower production costs would likely encourage farmers to cultivate switchgrass.

Climatic limitations are negligible in the study region and even where they occur are not strong limitations (capability classes II or III): land ranked "c" was only about 1% of the total land selected for the simulation (Figure 2). Switchgrass was then allocated on this land, following again the "economical/consensus" criterion, since none of the two crops seemed to have any significant ecological advantage.

2.3 | Regional simulation set-up and runs

Unique combinations of weather, soil type, and land use were identified within the study region. Each unique combination represented a DAYCENT modeling "strata," which is a distinct model run. Climate data were derived from the North American Regional Reanalysis (NARR) database (Mesinger et al., 2006) (32 km grid). To identify soils with different characteristics (sand and clay contents, pH, rock fragments, depth), the SSURGO database was used (Ernstrom & Lytle, 1993). For land use, the above mentioned National Land Cover Database (NLCD) 2006 (Wickham et al., 2013) was employed. In total, 106,340 unique combinations of weather, soil type, and land use were identified.

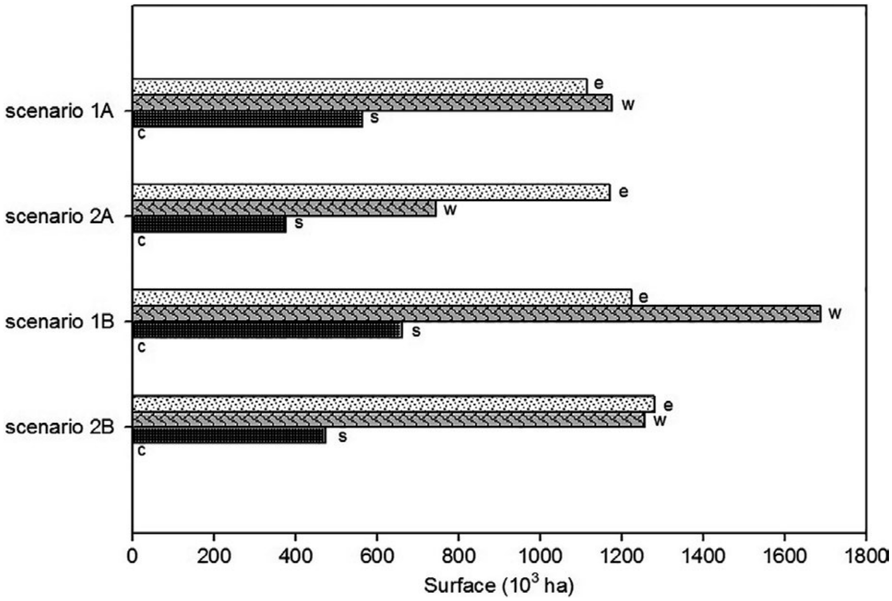

FIGURE 2 Within each simulated scenario in the U.S. Southeast, the total surface (10^3 ha) belonging to each subclass of the USDA capability classification is shown. Land ranked "e" is susceptible to erosion, land ranked "w" is subject to periodic flooding events; land ranked "s" has limitations within the rooting zone (i.e., shallowness, stones, low moisture-holding capacity, low fertility, salinity), land ranked "c" has climatic limitations (temperature or lack of moisture). The subclasses of the capability classification were used as criterion to allocate the biofuel crops switchgrass and giant reed

For each strata, the initial values of soil C and N were initialized by an equilibrium phase during which DAYCENT simulated, for several thousand years, what was assumed had been the historical land use (Ogle et al., 2010). The equilibrium phase was split in two parts: a first one, up to year 1850 (this phase extended to the present for grasslands), where the original natural vegetation was simulated and soil steady-state was reached, and a second one (only for croplands), up to the present, where first plow-out and crop rotations and managements were simulated according to various sources (Ogle et al., 2010).

Following the initialization, 15 years of cultivation of switchgrass or giant reed were simulated. Sowing of switchgrass seed and planting of giant reed rhizomes occurred in May, and harvest of the crops was carried out in October every year (harvest losses ~15%). The crops were not fertilized in the establishment year to avoid competition of weeds, whereas 67 kg N ha^{-1} year^{-1} were added from the second year on. This N fertilization rate was shown to be the most beneficial for switchgrass production in marginal areas, taking into account economical and environmental aspects (Wang et al., 2015). No such data on the best N fertilization rate for giant reed were found in the present literature, thus, also to facilitate a comparison between the two perennials after the simulation, the same amount of N was given to both crops.

2.4 | Sensitivity analysis of crop allocation

Two sensitivity analyses were performed, changing the allocation criteria for the two crops. In the first analysis, a part of the land cultivated with switchgrass was allocated to giant reed. Giant reed being more productive, the effect of this analysis was to narrow the biomass supply area around the potential new biorefineries and to possibly predict the position of other biorefineries (see the next section). So, this time, all land in capability subclass "s" was cultivated with giant reed instead of switchgrass. In the second analysis, the aim, differently from the previous analysis, was not to simulate more biomass production or to predict more potential biorefineries, but to simulate scenarios with a reduced invasion risk brought by giant reed. In fact, although the risk of giant reed invasion is low outside the riparian environments and it is further lowered by the annual harvest carried out when managed as an energy crop (Ceotto & Di Candilo, 2010), the invasion risk is higher in periodically flooded areas, since it "typically spread in riparian systems by flood-mediated fragmentation and dispersal of vegetative propagules" (Ceotto & Di Candilo, 2010; Herrera & Dudley, 2003). Therefore, in this second analysis, all land ranked "s" was cultivated with giant reed while all land ranked "w", where the risk of invasion is more probable, was cultivated with switchgrass (Table 4).

2.5 | Biorefineries position

Total mean yearly harvested biomass was calculated at the county level (1,001 counties in total). Then, using ArcMap 10.2.2 (ESRI), an analysis was carried out to discover the potential position of new biorefineries. We assumed the supply of bioethanol production plants with a capacity of 286 Ml ethanol/year. Although at present the biggest working biorefineries in the United States supplied by lignocellulosic feedstocks reach a capacity of 95 Ml ethanol/year (Bacovsky et al., 2013), in the future will be economically advantageous to build larger plants. This is feasible, taking into account that currently in the Unites States there are thirteen first-generation ethanol refineries with a capacity over 500S Ml

TABLE 4 Allocation rules for switchgrass (SG) and giant reed (GR), based on LCC subclass ratings

	e (erosion hazards)	w (flooding risks)	s (soil limitations)	c[a] (climate limitations)
Baseline	SG	GR	SG	SG
Sensitivity 1	SG	GR	GR	SG
Sensitivity 2	SG	SG	GR	SG

[a]Accounts for only 1% of the land in the study area.

ethanol/year, and three of them with a capacity over 1,000 Ml ethanol/year (EIA, 2017). Thus, we decided to use the average size of all working U.S. ethanol plants at present (286 Ml ethanol/year; EIA, 2017) as our target for future plants in the U.S. Southeast, which seemed a reasonable size. Such plants would demand ~1.02 Mt/year of dry biomass (under current technology, 282 L ethanol/Mg of dry biomass are to be produced; Lynd et al., 2008). An 80-km radius around the potential new biorefineries was used for biomass supply (20,096 km^2 of supply area), as it was estimated as the economically feasible transportation distance in Alabama, and various other southeastern States (Bailey, Dyer, & Teeter, 2011). In the first sensitivity analysis, where giant reed was allocated on more surface and where therefore we expected a higher biomass density (more biomass in most counties), also a 50-km radius for biomass supply was tested, according to IEA (2007).

To identify potential supply areas of 20,096 km^2, a moving window (Focal Statistic) included in ArcMap's "Neighborhood Toolset" was employed. The sum of the yearly yields of each spatial unit (1 ha) was calculated within the specified neighborhood (circles with an 80-km radius) of the simulation region: when the sum was equal to 1.02 Mt/year of dry biomass or higher, that specific neighborhood was designed as potential supply area of a biorefinery. Biomass within a supply area was then considered sufficient (between 1.02 and 1.3 Mt/year), abundant (>1.3 Mt/year) or very high (>2.1 Mt/year). This analysis was performed for each of the baseline scenarios and for each scenario resulting from the two sensitivity analyses, to finally compare their potential to produce bioethanol in the U.S. Southeast.

2.6 | Greenhouse gas accounting

Starting from the model outputs, SOC changes and system N losses were converted in total GHG emissions (CO_2 equivalents, including both direct and indirect biogenic sources) as follows (IPCC 2014):

$$Co_2\text{eq} = -(\text{SOC change} \times 3.67) \tag{1}$$

$$Co_2\text{eq} = [(\nu N \times 0.01) + (lN \times 0.0075) + (\text{NO} \times 0.01) + N_2O] \times 298 \tag{2}$$

where νN is the volatilized nitrogen, lN is the nitrogen leached and NO is nitric oxide; negative values correspond to a GHG uptake, whereas positive values correspond to a GHG emission.

Greenhouse gas intensity was calculated as the ratio between GHG emissions and dry biomass yield.

3 | RESULTS

3.1 | Simulation of switchgrass and giant reed in the U.S. Southeast

Mean simulated long-term (15 years) yields were, across the study region, higher for giant reed (16.3 Mg ha^{-1} year^{-1}) than switchgrass (7.9 Mg ha^{-1} year^{-1}), and higher on former grazing land than on former croplands, especially when switchgrass was cultivated (+14%); this was likely due to the fertilizing effect of the aboveground residues embedded in the soil upon conversion, as well as to the fact that only croplands that were marginal, thus with lower yield potential, were converted. Mean SOC change after 15 years of cultivation was significantly positive after croplands conversion (0.27 and 0.57 Mg ha^{-1} year^{-1}, respectively, for switchgrass and giant reed), whereas it was negative or null after grazing land conversion (−0.23 and 0.01 Mg ha^{-1} year^{-1}, respectively, for switchgrass and giant reed). Mean N_2O emissions did not differ much between the two crops and between distinct land use transitions (1.6–1.9 kg ha^{-1} year^{-1}, on average), since N fertilization, the main trigger of N_2O emissions in agriculture (Del Grosso et al., 2006; Erisman et al., 2010), was maintained constant in each simulation strata.

Giant reed long-term yields fluctuated more than switchgrass long-term yields across States: the lowest yields, on average, were achieved in Virginia (7.7 and 12.9 Mg ha^{-1} year^{-1}, respectively, for switchgrass and giant reed), whereas the highest yields, on average, were reached in Louisiana (8.6 and 18.1 Mg ha^{-1} year^{-1}, respectively, for switchgrass and giant reed). In general, lower yields were simulated in Virginia, North Carolina, and Kentucky for both crops, whereas higher yields were simulated in Louisiana, Mississippi, Alabama, and Florida for giant reed, or in Louisiana, South Carolina, Georgia, Mississippi for switchgrass. A latitudinal gradient within the U.S. Southeast was evident in giant reed productivity: average giant reed yields, in fact, varied by 40% passing from Virginia to Louisiana, whereas varied by only 11% in switchgrass; this temperature dependence of giant reed well agrees with the literature that describes giant reed as a warm-temperate or subtropical species (Lewandowski et al., 2003).

DAYCENT was able to simulate lower productivity on marginal land. Mean yields on marginal cropland within the simulation region (Table 5; 7.4 and 16.2 Mg ha^{-1} $year^{-1}$ for switchgrass and giant reed, respectively) were lower than mean yields simulated during the calibration/evaluation process for switchgrass (only U.S. studies, 14.4 Mg ha^{-1} $year^{-1}$, 95% higher) or giant reed (25.0 Mg ha^{-1} $year^{-1}$, 55% higher) on conventional (nonmarginal) croplands where similar N fertilization rates were applied (between 50 and 100 kg ha^{-1} $year^{-1}$; Hidalgo & Fernandez, 2000; Kering et al., 2012; Cosentino et al., 2014; Monti & Zegada-Lizarazu, 2015; Nocentini et al., 2015).

3.2 | LUC scenarios

Summing up total areas cultivated with switchgrass and giant reed, 2.9, 2.4, 3.6, and 3.1 Mha of the study region were converted, respectively, in scenarios 1A, 2A, 1B, and 2B (Figure 3). The corresponding total dry biomass production, total SOC variation, and total N_2O emissions for each scenario are reported on a yearly basis in Table 6.

Converting poor grazing land (scenarios 1A and 1B) was more efficient than converting good grazing land (scenarios 2A and 2B) in terms of dry biomass production and SOC change per hectare, but this was due to the allocation strategy adopted between the two crops. In scenario 1A less land was ranked "e" and more land was ranked "w" compared to scenario 2A. Thus, in scenario 1A and 1B, respectively, the 41 and 47% of the surface was cultivated with giant reed, whereas, in scenario 2A and 2B, less surface was dedicated to giant reed (respectively, 32 and 41%). As shown in the previous section, higher long-term yields were simulated for giant reed than switchgrass on average (+99%) and, moreover, when converting grazing land, giant reed was neutral to beneficial while switchgrass lost SOC: therefore, more land dedicated to giant reed meant more benefits in terms of GHG savings.

Compared to only grazing land conversion (scenarios 1A and 2A), adding former croplands to biomass production turned soils from a source to a sink of C (scenario 1B). In fact, the conversion of 0.7 Mha of croplands produced a SOC gain of the magnitude of 0.40 Mt/year (0.57 Mg ha^{-1} $year^{-1}$, on average), whereas grazing land conversion (5.3 Mha) produced a SOC loss of −0.79 Mt/year (−0.15 Mg ha^{-1} $year^{-1}$, on average).

We also estimated the C debt deriving from the loss of permanent aboveground vegetation after conversion of grazing land. This conversion debt corresponded to −0.67 Mg (C) per ha on average. However, we considered this C debt abundantly counterbalanced by the enormous root biomass production of switchgrass and giant reed, corresponding, respectively, to 2.4 and 3.9 Mg (C) per ha on average in the mature stands.

After performing the first sensitivity analysis (giant reed cultivation was expanded on all subclass "s" land; Table 6), the 61 and 66% of the surface, respectively, in scenarios 1A and 1B, were converted to giant reed, while it was cultivated on the 48 and 56% of the surface, respectively, in scenarios 2A and 2B. Compared to the baseline scenarios, in the new scenarios an increase in total biomass production was evident (+11% to 15%), less SOC (−18% to −37%) was lost after grazing land conversion (scenarios 1A and 2A, respectively) and both, scenarios 1B and 2B, registered positive SOC gains (0.21 and 0.07 Mt/year, respectively). On the contrary, total N_2O emissions were not significantly affected by the change in crop allocation.

In the sensitivity analysis aimed to minimize giant reed's invasion risks (switchgrass planted on "w" subclass land and giant reed on "s" land), giant reed was cultivated, depending on the scenario, on the 15%–20% of the surface converted, thus on much less land than in the baseline scenarios (Table 6). This change in crop allocation caused a reduction in biomass production (−12% to −20%) and made each scenario result in a greater SOC loss, even scenario 1B, which had a positive SOC gain in the previous two analyses, lost SOC (−0.29 Mt/year).

Again, in both re-allocations of the two crops, scenarios 1A and 1B were more efficient in terms of biomass production and SOC change than scenarios 2A and 2B. This can finally be explained by the higher amount (+5%) of land ranked "e" in good (scenario 2A) than in poor (scenario 1A) grazing lands (land ranked "e" was cultivated in all the analyses with switchgrass, which yielded less than

TABLE 5 Mean long-term yield, peak yield (reached in the second or third year after establishment, respectively, in switchgrass and giant reed), mean SOC change and mean N_2O emissions for switchgrass (SG) and giant reed (GR) cultivated in the U.S. Southeast after conversion of either grazing land or marginal croplands

Crop	Former land use	Mean yield (Mg ha^{-1} $year^{-1}$)	Peak yield (Mg ha^{-1} $year^{-1}$)	Mean SOC change (Mg ha^{-1} $year^{-1}$)	Mean N_2O emissions (kg ha^{-1} $year^{-1}$)
SG	Grassland	8.4	24.2	−0.23	1.9
GR	Grassland	16.5	28.8	0.01	1.7
SG	Cropland	7.4	21.3	0.27	1.7
GR	Cropland	16.2	28.4	0.57	1.6

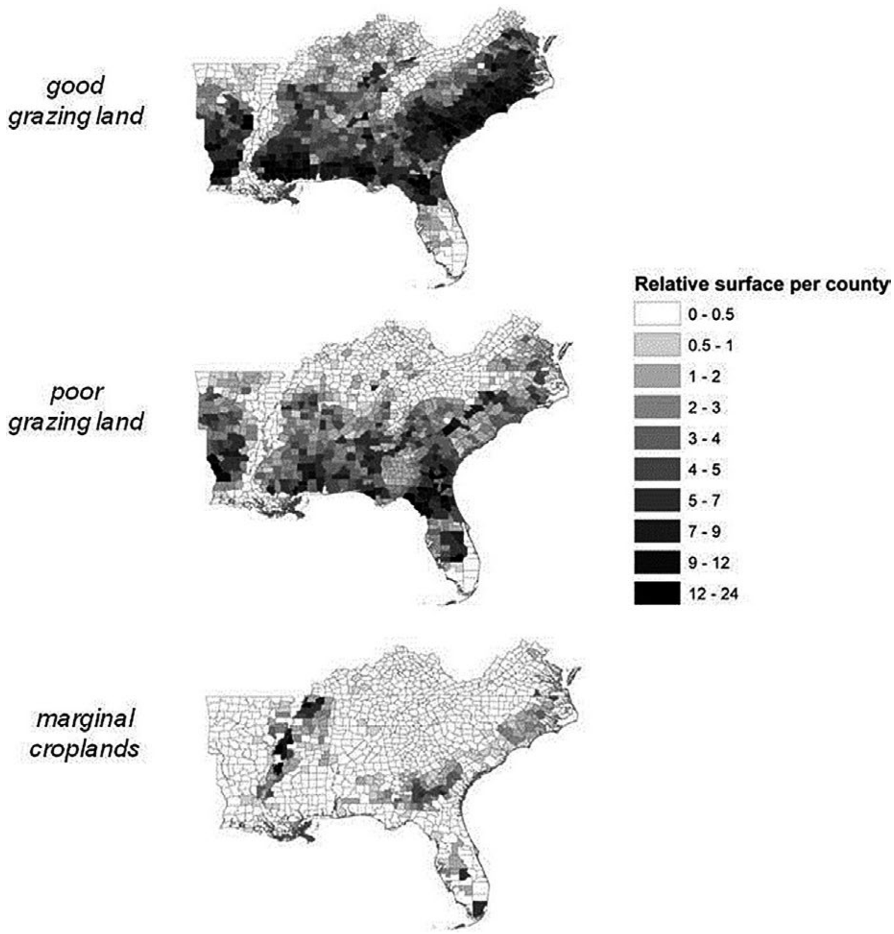

FIGURE 3 For each county of the U.S. Southeast, shows the relative part (%) of the total county surface occupied by good grazing land (grasslands and shrublands in capability classes I, II, III), poor grazing land (grasslands and shrublands in capability classes IV, V, VI) and marginal croplands (croplands in capability classes V and VI)

TABLE 6 Total dry biomass production, total SOC variation and total N_2O emissions for the scenarios simulated in the U.S. Southeast. Scenarios 1A (conversion of poor grazing land), 2A (conversion of good grazing land), 1B (conversion of poor grazing land plus conversion of marginal croplands) and 2B (conversion of good grazing land plus conversion of marginal croplands) differed in the selection of the land where the biofuel crops switchgrass and giant reed were allocated. Besides the baseline scenarios, results after giant reed expansion (1st sensitivity analysis) and after reallocation of giant reed to minimize invasion risks (2nd sensitivity analysis) are shown. Allocation of switchgrass (%) is complementary to giant reed allocation

Scenario	Surface (Mha)	Allocation (giant reed %)	Dry biomass (Mt/year)	SOC change (Mt/year)	N_2O emissions (Mt/year)
1A (baseline)	2.9	41	34	−0.35	0.005
2A (baseline)	2.4	32	26	−0.44	0.004
1B (baseline)	3.6	47	44	0.05	0.007
2B (baseline)	3.1	41	36	−0.04	0.006
1A (1st sensitivity)	2.9	61	39	−0.22	0.005
2A (1st sensitivity)	2.4	48	29	−0.36	0.004
1B (1st sensitivity)	3.6	66	49	0.21	0.007
2B (1st sensitivity)	3.1	56	40	0.07	0.006
1A (2nd sensitivity)	2.9	20	29	−0.54	0.005
2A (2nd sensitivity)	2.4	16	23	−0.56	0.005
1B (2nd sensitivity)	3.6	19	35	−0.29	0.007
2B (2nd sensitivity)	3.1	15	29	−0.31	0.006

giant reed and was detrimental on SOC when replacing grasslands).

3.3 | Biorefineries potential position

The highest biomass concentration was simulated in scenario 1B (Figure 4a), where Ware County (GA) produced enough biomass in its surroundings (20,096 km^2) to supply a bioethanol plant with a capacity of 838 Ml ethanol/year. Across the different scenarios, Florida, Georgia, Mississippi and South Carolina were the States with the highest biomass supply potential, which means with high land availability too. Table 7 summarizes some of the data resulting from the GIS analysis regarding the maximum number of bioethanol plants and the counties with the highest biomass supply potential in each baseline scenario.

Conversion of good grazing land performed worse than the conversion of poor grazing land. In fact, despite a −17% of land converted to biofuel production, a maximum number of seven bioethanol plants was estimated for scenario 2A, whereas up to 12 bioethanol plants could be built in scenario 1A. If we were to convert only marginal croplands (scenario B), Mississippi would still have the potential to supply up to three bioethanol plants and Washington County (MS) could supply a bioethanol plant with a capacity of 462 Ml ethanol/year.

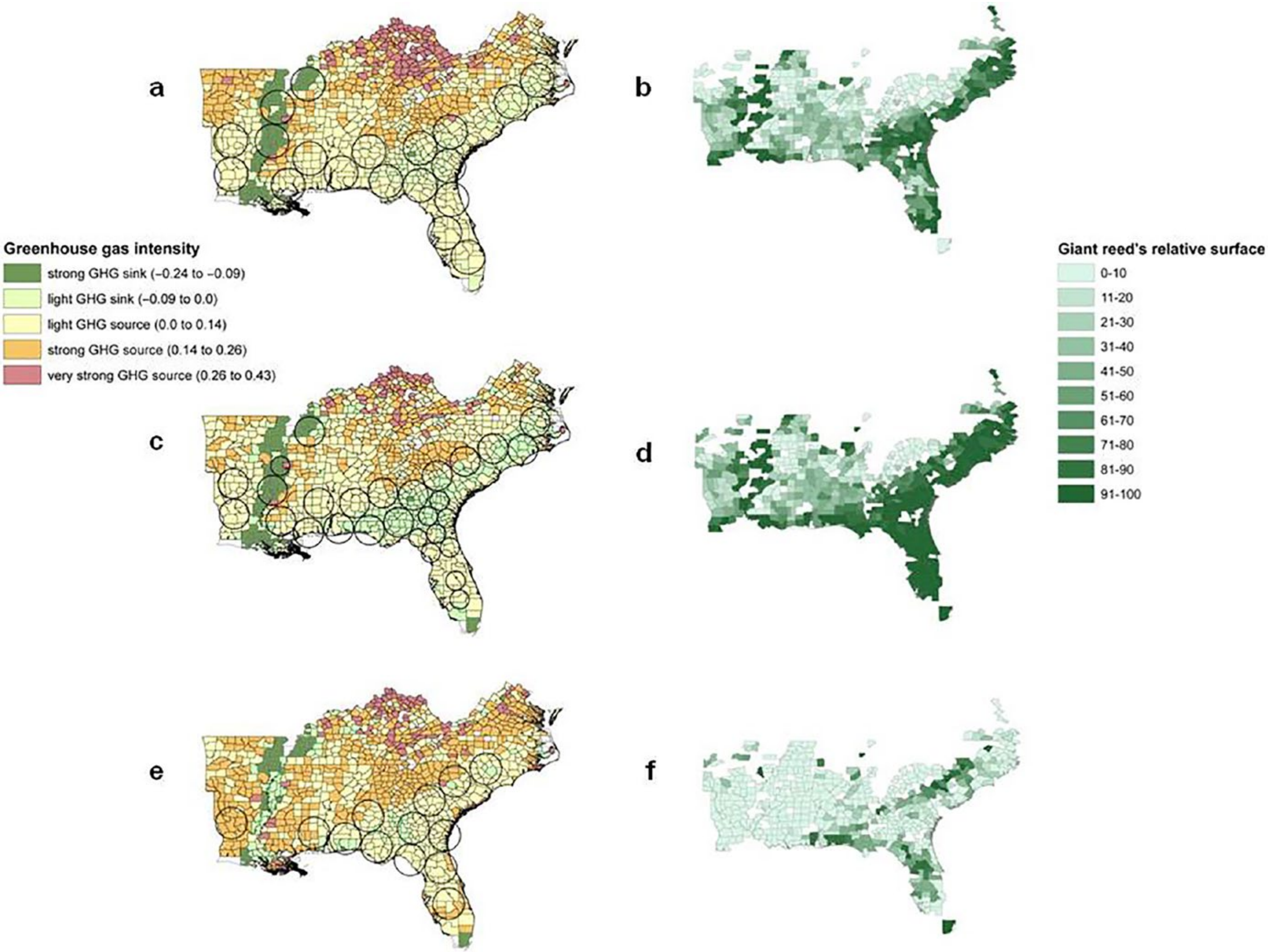

FIGURE 4 (a) Greenhouse gas intensity (Mg CO_2eq/Mg of dry biomass) for each county of the U.S. Southeast in scenario 1B (conversion of poor grazing land plus conversion of marginal croplands); (b) Giant reed's relative surface (%) respect to the total surface converted to bioethanol production for each county of the U.S. Southeast in scenario 1B; (c) Greenhouse gas intensity for each county of the U.S. Southeast in scenario 1B after giant reed expansion (first sensitivity analysis of crop allocation); (d) Giant reed's relative surface respect to the total surface converted to bioethanol production for each county of the U.S. Southeast in scenario 1B after giant reed expansion (first sensitivity analysis of crop allocation); (e) Greenhouse gas intensity for each county of the U.S. Southeast in scenario 1B after giant reed contraction (second sensitivity analysis of crop allocation); (f) Giant reed's relative surface respect to the total surface converted to bioethanol production for each county of the U.S. Southeast in scenario 1B after giant reed contraction (second sensitivity analysis of crop allocation). Potential biomass supply areas for average size bioethanol plants (286 Ml ethanol/year) are identified by 80-km radius circles in subfigures a and e, and identified by 80-km or 50-km radius circles in subfigure c. In subfigures b, d and f only counties with at least 2000 ha converted to bioethanol production are shown

Expanding giant reed cultivation greatly increased biomass production (Table 6). So that up to six or ten bioethanol plants could be supplied within a smaller radius (50 km), respectively, in scenarios 1A and 1B (Figure 4c). The conversion of solely marginal croplands (scenario B), still produced enough biomass (~1.05 Mt/year) for an average size bioethanol plant in Sunflower County (MS) that could be supplied within a 50-km radius. The districts with the highest potential were identified, similar to the previous analysis, in northern and central Florida (Columbia, Suwannee, Lafayette, Gilchrist, and Highlands counties), in southern Georgia (Ware and Bacon counties), and western Mississippi (Sunflower County). This sensitivity analysis further underlined the outstanding capacity of giant reed to function as a bioenergy feedstock.

Reducing the area cultivated with giant reed to minimize its invasion risks also reduced the potential for bioethanol production in each scenario. Nonetheless, scenarios 1A and 1B maintained very high or abundant biomass supplies in northern Florida, southeastern Georgia, and southern Alabama (Figure 4e); Columbia (FL) and Alachua (FL) counties showed very high biomass availability (~2.4 Mt/year) in their surroundings. Scenarios 2A and 2B yielded biomass just sufficient (<1.3 Mt/year) for, respectively, seven or nine bioethanol plants in southern South Carolina, eastern Georgia, northern Florida, and southern Mississippi, with only Screven (GA) and Allendale (GA) counties showing abundant biomass supplies (~1.4 Mt/year). While in the baseline scenarios converting to biomass production only marginal croplands was still sufficient to supply up to three ethanol plants (two in eastern Mississippi and one in southern Georgia), after changing crop allocation to minimize giant reed invasion risk, that was not achievable anymore and only smaller biorefineries (140–200 Ml/year) could be eventually built in western Tennessee or western Mississippi.

Table 7 shows that the conversion of poor grazing land plus the conversion of marginal croplands (scenario 1B) had the highest ethanol productivity potential. In this scenario, 7,124 Ml/year of advanced ethanol from nineteen biorefineries (Figure 4a) could be produced, with some supply areas (two in western Mississippi and one in western Tennessee) also working as GHG sinks thanks to SOC storage. After confining giant reed to minimize invasion risks, 4,695 Ml/year could be still produced from thirteen biorefineries (Figure 4e), but, this time, all the supply areas turned into a soil GHG source. When instead giant reed cultivation was expanded, up to 28 biorefineries could be supplied (Figure 4c), with a total ethanol production of 9,743 Ml/year, and ten of these biorefineries could be supplied within a 50-km radius, thus allowing a reduction in the emissions caused by the transportation of the biomass to the transformation plants (IEA 2007); further, in this latter case, 36% of the supply areas (two in northern Florida, four in southern Georgia, two in western Mississippi, one in western Tennessee, and one in southern North Carolina) would operate as GHG sinks.

4 | DISCUSSION

The southeastern United States has the potential to host several large biorefineries that produce advance ethanol from marginal land, but the associated soil GHG emissions depend on whether switchgrass and giant reed are planted on former grazing lands or croplands. This study also showed that (i) switchgrass and giant reed had different impacts on SOC stocks, especially when cultivated on former grazing land, (ii) the States that could host several large size plants for the production of advanced ethanol were, principally, Florida, Georgia, South Carolina, and Mississippi, (iii) among all scenarios, 1B (conversion of poor grazing land plus conversion of marginal croplands) resulted as the most beneficial option, considering both ethanol productivity and soil GHG impact (iv) favoring giant reed cultivation could lead to significant GHG benefits in the whole region, whereas contracting giant reed cultivation in order to minimize invasion risks would still allow a substantial production of advanced ethanol, though most supply areas would turn into a soil GHG source.

Analyzing different land use change options underscored the distinct potentials of switchgrass and giant reed. Although at a different rate, both crops increased SOC after replacing marginal croplands (0.27 and 0.57 Mg ha^{-1} year^{-1}, respectively, in switchgrass and giant reed) and thus had a positive impact, but when grasslands and shrublands were converted, the impacts differed: on average, switchgrass lost

TABLE 7 For each baseline scenario, the maximum number of potential bioethanol plants with an 80-km radius supply area, the highest biomass supply within the radius and the counties with the highest biomass production potential are presented

Scenario	1A	2A	1B	2B	B
Biorefineries (number)	12	7	19	16	3
Highest supply (Mt)	2.92	1.41	2.97	1.79	1.64
Top counties	Columbia (FL) Suwannee (FL) Gilchrist (FL)	Berkeley (SC) Orangeburg (SC) Colleton (SC)	Ware (GA) Columbia (FL) Suwannee (FL)	Washington (MS) Bladen (NC) Sunflower (MS)	Washington (MS) Sunflower (MS) Coahoma (MS)

SOC, whereas giant reed was neutral (−0.23 and 0.01 Mg ha^{-1} year^{-1}, respectively), meaning that only giant reed was able to recover the initial SOC loss occurring upon grasslands conversion and to maintain it in the long term. Interestingly, Qin et al. (2016), after a meta analysis on SOC storage by biofuel crops, reported similar results comparing switchgrass with the higher yielding miscanthus: they found that, after grasslands conversion, on average, the former lost SOC (−0.16 Mg ha^{-1} year^{-1}), whereas the latter showed a positive SOC gain (0.28 Mg ha^{-1} year^{-1}). In this study, giant reed cultivation allowed for greater biofuel production and lower soil GHG emissions. In fact, an evident pattern was observable (Figure 4): the counties with a higher proportion of land converted to giant reed were the counties with the highest biomass supplies and where greenhouse gas intensity assumed negative values, which corresponded to a GHG uptake.

We must stress the fact that, in the current analysis, life-cycle GHG impacts were not accounted for, since it was out of the scope of this work. However, for each Mg of dry herbaceous biomass transformed in advanced ethanol, 0.53 Mg of CO_2eq could be saved as fossil fuel offset credits (GREET model; Gelfand et al., 2013). At the same time, life-cycle emissions due to the use of agronomic inputs would correspond to 0.74 and 1.10 Mg of CO_2eq to cultivate one hectare of switchgrass or giant reed, respectively (Fazio & Monti, 2011). For example, in the case of switchgrass being established on former grazing land, which was the worst performing option in terms of soil GHG emissions (Table 5), applying the coefficients reported above (Fazio & Monti, 2011; Gelfand et al., 2013), on average, soil and life-cycle GHG emissions would correspond, respectively, to 1.41 and 0.74 Mg of CO_2eq ha^{-1} year^{-1}, whereas emissions savings due to fossil fuel offset would correspond to 4.45 Mg of CO_2eq ha^{-1} year^{-1}. Moreover, we focused the analysis on scenarios that would avoid displacing highly productive agriculture and thus minimize ILUC effects (Searchinger et al., 2008), though precise quantification of any such remaining impacts is also outside the scope of the current analysis.

Table 7 shows the States of Florida, Georgia, South Carolina, and Mississippi having a high potential for advanced ethanol production, so, analyzing more deeply the land uses of these four States, we find that Florida and Georgia together had 38% of total poor grazing land of the simulation region, South Carolina had 12% of total good grazing land, whereas Mississippi and Georgia together had 44% of total marginal croplands. Cai et al. (2011) also showed Florida, Georgia, South Carolina, and Mississippi to have high land availability (from map), when considering marginal/abandoned croplands and grasslands discounted by the grazing land at present.

Our analysis, as our previous DAYCENT simulation work in the Mediterranean basin (Nocentini et al., 2015), resulted in a basic difference in soil emissions between land use change strategies. On average, SOC increased when converting croplands while decreased when converting grasslands and shrublands (0.57 and −0.15 Mg ha^{-1} year^{-1}, respectively). In those scenarios that combined the conversion of grazing land and croplands (1B and 2B), total N_2O emissions were always more important than total changes in SOC storage when expressed as CO_2eq, because of the predominance of former grazing land (which is a strong N_2O source but had little change in SOC). On the opposite, when converting only marginal croplands, the GHG sink due to SOC storage (−1.48 Mt CO_2eq/year) was significantly higher than the GHG emissions as N_2O (0.42 Mt CO_2eq/year). The literature already reports that SOC storage is foreseeable when converting croplands to biofuel perennial crops (Davis et al., 2012; Fargione et al., 2008; Qin et al., 2016), whereas less predictable SOC dynamics occur after converting unmanaged systems (Corre, Schnabel, & Shaffer, 1999; Garten & Wullschleger, 2000; Qin et al., 2016), since they usually have a higher initial SOC concentration. Consistent with our results, for example, Davis et al. (2012) found that cultivating perennial biofuel feedstocks on croplands currently cultivated with corn (used for bioethanol) could greatly reduce GHG emissions (−29% to −473%). Qin et al. (2015), after simulating lignocellulosic feedstocks cultivation on U.S. marginal land, found both switchgrass and miscanthus being a GHG source with intensity of 100–390 or 21–36 g CO_2eq/L of ethanol, respectively, but they did not distinguish between distinct former land uses. In contrast, our study showed a GHG intensity of −232 to 595 and −353 to 101 g CO_2eq/L for switchgrass or giant reed, respectively, with the gap depending on the land use change, and underlying the distinct potential of grassland versus cropland conversion. Although in the scenarios including grazing land conversion N_2O emissions significantly impacted GHG emissions, on average (477–566 kg CO_2eq ha^{-1} year^{-1}) they were lower than N_2O emissions from agricultural soils cultivated with annuals and comparable with those from other perennial crops (Don et al., 2012; Drewer, Finch, Lloyd, Baggs, & Skiba, 2012; Gelfand, Shcherbak, Millar, Kravchenko, & Robertson, 2016). Model calibration was, however, in part hindered by the lack of data on N_2O emissions in giant reed; this knowledge gap should be addressed in future research.

In addition, when converting unmanaged grasslands and shrublands, no matter how low-input the succeeding biofuel crop may be, management-related GHG emissions will increase. On the opposite, when converting croplands, emissions from agronomic inputs are likely to diminish (Adler et al., 2007; Fazio & Monti, 2011; Gelfand et al., 2013), together with N_2O emissions following the lower N fertilization rates given to perennial crops (Del Grosso et al., 2006; Drewer et al., 2012). The sustainability of land use change also depends on plant diversity and wildlife refuges, which are likely to be reduced upon grasslands and shrublands conversion but to be enhanced with the establishment of switchgrass or giant reed on former tilled croplands (Fernando, Duarte, Almeida, Boléo, & Mendes, 2010).

The best scenario resolved in this study for advanced cellulosic feedstock production was one that includes the conversion of marginal croplands: among the simulated scenarios that included conversion of croplands, we selected scenario 1B (conversion of poor grazing land plus conversion of marginal croplands) as the most beneficial, considering the biomass productivity per hectare and soil GHG emissions (Table 6). In fact, scenario B (only conversion of marginal croplands), although highly beneficial as GHG sink, was deficient in terms of land availability (a high land availability that would allow a substantial production of ethanol was only found in Mississippi), whereas scenario 2B (conversion of good grazing land plus conversion of marginal croplands) performed worse than 1B in terms of mean biomass yield, mean SOC storage rate and also mean N_2O emissions (Table 6), and resulted in a lower biofuel production within the region (Table 7). One likely explanation for the lower performance of scenario 2B compared to scenario 1B is that the former had a higher share of land where switchgrass was allocated (Table 6), thus with lower yields and depleted SOC stocks on former grazing land.

Scenario 1B could produce the ~8% (7,124 Ml/year) of the year 2022 cellulosic biofuel mandate of 16 billion gallons per year of gasoline equivalent (Renewable Fuel Standard; The Energy Independence and Security Act, 110th Congress of the United States, 2007); this contribution would reach the ~11% if expanding giant reed cultivation.

Currently there are five working bioethanol plants in the study region (EIA, 2017): Ergon Biofuels LLC (Vicksburg, Mississippi; 204 Ml/year), Flint Hills Resources LP (Camilla, Georgia; 454 Ml/year), Green Plains Obion LLC (Obion, Tennessee; 416 Ml/year), Commonwealth Agri-Energy (Hopkinsville, Kentucky; 114 Ml/year) and Green Plains Hopewell LLC (Hopewell, Virginia; 235 Ml/year). All these five plants are supplied by corn ethanol feedstocks but, if converted to the production of advanced ethanol from perennial lignocellulosic feedstocks, great GHG benefits could be achieved (Davis et al., 2012), while alleviating some of the ILUC impact by diverting corn back to the food market. For example, these results show that the Vicksburg plant, if only being supplied by switchgrass and giant reed cultivated on marginal land within an 80-km radius (scenario 1B), could produce even more ethanol (291 Ml/year) than it currently does, while fixing 1.1 Mt CO_2eq/year through SOC storage (Figure 4a). As for Camilla, Obion and Hopewell plants, respectively, 1.1, 0.9, and 0.5 Mt/year of dry biomass would be available in their surroundings (scenario 1B), and could substantially contribute to their ethanol production, after switching to advanced ethanol technologies.

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CONFLICT OF INTEREST

None declared.

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