Evaluating the potential of marginal lands available for sustainable cellulosic biofuel production in Italy

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ABSTRACT

The European Union aims to provide as much as one quarter of its transportation fuels via biofuels derived from renewable sources by 2030. To put this into perspective, the Italian government has recently established an ambitious goal to support the wider uptake of advanced second-generation biofuels, including cellulosic biofuels for the transportation sector. A sustainable way forward is to grow perennial biomass crops on marginal lands, however the nationwide availability of those lands for lignocellulosic feedstock production remains uncertain. We identify and evaluate the potential of marginal lands in Italy to produce sizeable amounts of biomass for sustainable cellulosic biofuel production while limiting land use conflicts and negative ecological impacts. We applied spatial multi-criteria decision analysis techniques in geographic information systems to ultimately generate spatially-explicit national land suitability and availability maps at a fine resolution (250-m). A broad range of leading cellulosic biomass crops, including poplar (*Populus* × *canadensis*), willow (*Salix alba*), black locust (*Robinia pseudoacacia*), giant reed (*Arundo donax*), and vetiver grass (*Chrysopogon zizanioides*) was used in our study. Based on marginality criteria, our results suggest that such biomass plantations of perennial grasses and short rotation trees may produce 3.1–27.4 billion liters of cellulosic ethanol per year from 462,265–2,811,064 million hectares of available marginal lands and may fulfill 7.8–69.1 per cent of Italy's current liquid transportation fuel consumption, constrained by the requirement that each modelled location be within 70 kilometers of a potential cellulosic biorefinery. Collectively, this study provides the cornerstone of efforts to rationally meet Italy's need for renewable fuels in a sustainable low-carbon economy future.

Keywords

cellulosic feedstocks, environmental sustainability, land availability, perennial grasses, renewable bioenergy, short rotation trees

1. Introduction

Globally, there is a growing interest in renewable and sustainable energy sources in an attempt to reduce further increases in greenhouse gases (GHG) emissions from the transport sector. European legislation (Directive 2018/2001) mandates the production of at least 14% of liquid transportation fuel as advanced biofuels from non-grain sources including, among others, lignocellulosic biofuels by every European Union (EU) country by 2030 (European Parliament, 2018).

Today, with environmental and societal policies pushing for a reduction of GHG emission and promoting clean energy, more sustainable transport fuels such as cellulosic biofuels have once again become viable and desirable surrogates for petroleum-based fuels, not to mention transportation sectors in which electrification will remain challenging (aviation, maritime).

The EU's Green New Deal (European Commission, 2019) aims to respond to the escalating climate crisis by achieving net zero GHG emissions by 2050 and aspires to protect human health from environment-related risks (Haines and Scheelbeek, 2020). Use of cellulosic biofuel, crucial for mitigating climate change, made from agricultural residues alone cannot ensure these ambitions are realized for the benefit of our health and the environment; to succeed, the EU will need to carefully evaluate and amend its green policies to include lignocellulosic biomass feedstocks. Also, the Green Deal risks becoming a bad deal for the planet if the EU continues to depend heavily on agricultural imports that are not produced sustainably (Fuchs et al., 2020).

Perennial lignocellulosic bioenergy crops provide an alternative to annual grains that increases biodiversity of multiple taxa and sustain a variety of ecosystem functions, promoting the creation of multifunctional agricultural landscapes (Werling et al., 2014). Cellulosic feedstocks can also have positive environmental outcomes (Meehana et al., 2010; Robertson et al., 2011) and could make up a substantial proportion of future renewable and sustainable energy portfolios (Ohlrogge et al., 2009). Producing bioenergy crops on marginal lands could help meet energy goals while minimizing competition with food production. Biophysical studies suggest that converting the land use from annual to perennial cropping is beneficial for restoring degraded soil (Fernando et al., 2018; Paustian et al., 2016). Mapping available lands for lignocellulosic biomass production is essential to land use planning efforts that aim to model and more comprehensively analyze trade-offs between economic development and the environment (Oakleaf et al., 2019).

Global projections indicate that the biomass demand to sustain bio-based production chains will amount to 6.7–13.4 billion tons per year in 2050, with an increase of 198–396% compared to 2011 levels (3.4 tons per year) (Piotrowski et al., 2015). Dedicated bioenergy crops are being sought to produce high-yielding lignocellulosic biomass (Clifton-Brown et al., 2019). Furthermore, data from several studies indicate mixtures of perennial lignocellulosic biomass crops grown on marginal lands under low-input agriculture as suitable cropping systems for biomass production (Carlsson et al., 2017; Mehmood et al., 2016; Robertson et al., 2017). Relying on energy sources derived from lignocellulosic biomass crops that include productive perennial grasses and fast-growing trees, rather than on first generation biofuels based on grain or high-sugar crops, is a pivotal option of climate change mitigation solutions as biomass can be essentially substituted for the use of fossil fuels.

The use of marginal lands for growing bioenergy crops is widely recognized as an effective solution for both limiting possible land-use conflicts among food, energy and environment, the so-called food, energy, environment trilemma (Manning et al., 2015; Solinas et al., 2015; Tilman et al., 2009), and offering a higher technical potential compared to other biomass feedstocks derived from wastes and residues of other sectors, including agriculture, forestry and aquaculture (Schneider et al., 2001). In other words, the use of marginal lands for bioenergy crops provides a win-win solution to the above mentioned trilemma in a truly circular bioeconomy perspective (Duvernoy et al., 2018; Kelly et al., 2015; Zitti et al., 2015).

Earlier studies were devoted to assess apparent and latent relationships between land abandonment, rural development, and economic marginality in both advanced and emerging countries (Campbell et al., 2008; Edrisi and Abhilash, 2016; Mehmood et al., 2016; Sallustio et al., 2018). However, only few evaluated challenges and opportunities related to bioenergy production. In the EU, the potential impact of agricultural and trade policy reform on land-use was analyzed focusing mainly on land abandonment (Kluts et al., 2017). Under removal of Pillar 1 supporting payments and trade liberalization, around 8% less land is expected to be farmed with areas and farm types facing more significant reductions in specific regions. Decline and loss of state subsidies for agriculture from 1990 to 2000 was an underlying cause for the decrease of cultivation in economically-marginal rural areas, indicating that macro-scale forces overall fostered cropland abandonment in connection with place-specific drivers (Biasi et al., 2015; Ferrara et al., 2017).

In this regard, the value of spatially-explicit models for studying the determinants of land-use and land-cover change in large areas is particularly high when distinguishing the importance of micro-scale and macro-scale drivers of cropland abandonment (Sallustio et al., 2018). Land suitability and availability for bioenergy crops have been investigated at national and regional scales with a specific focus on marginal lands (Aust et al., 2014; Crawford et al., 2016; Edrisi and Abhilash, 2016). Multi-criteria decision analysis (MCDA) has been recognized as a valuable approach exploring benefits and constraints of different land-use alternatives, and has been widely used to solve controversial situations (e.g., land-use conflicts) such as those dealing with nature conservation targets (Adem Esmail and Geneletti, 2018). MCDA approaches have been extensively adopted in land suitability assessment for their pivotal role in supporting decision making processes (Global Bioenergy Partnership, 2010; Lewis and Kelly, 2014; Nisar Ahamed et al., 2000).

With special regard to the food versus fuel debate (Shortall, 2013), fallow land is demonstrated to represent a sort of land stock available for alternative use (Allen et al., 2015; Fiorese and Guariso, 2010), whose multiple values (economic, ecological, social) are recognized in earlier studies worldwide (Aust et al., 2014; Edrisi and Abhilash, 2016; Lovett et al., 2014; Mehmood et al., 2016). Alternative use for fallow land was extensively discussed (Lewis et al., 2015; Lewis and Kelly, 2014; Nisar Ahamed et al., 2000; Rodríguez et al., 2017), under a comprehensive analysis of regional and place-specific contexts for a given land destination.

At a global scale, a study by Cai, Zhang, & Wang (2011) estimated that about 320−1411 million hectares of marginal lands in Africa, India, Europe, China, South America, and the continental United States, are available for bioenergy crops depending on different scenarios. According to the study, marginal lands availability in Europe might range between 33 and 111 million ha, with a potential contribution to the global liquid fuel consumption ranging between 10% and 24%. Although the wide range of small-scale studies (Delivand et al., 2015; Messineo et al., 2012; Nikodinoska et al., 2017) and the leading role of bioenergy in high-tech environment and bio-based industry (de Arano et al., 2018; Italian agency for territorial cohesion, 2016), broad-scale, spatially-explicit studies on land availability for bioenergy crops are currently lacking in Italy. Lack of information currently represents a constraint for development of national strategies able to emphasize the future role of lignocellulosic biofuel feedstocks, which still remain an open challenge to development (Italian agency for territorial cohesion, 2016; Lewis and Kelly, 2014; Monti and Cosentino, 2015).

Based on these premises, our study (Fig. 1) aims at evaluating: (i) the potentially available marginal agricultural lands for cellulosic biomass crops cultivation in Italy; (ii) the amount and spatial location of potential biomass availability for cellulosic biorefineries; and (iii) how much of Italy's current liquid transportation fuel consumption could potentially rely on cellulosic biofuels. Land suitability for three dedicated biomass woody crops, poplar (*Populus* × *canadensis*), white willow (*Salix alba*), and black locust (*Robinia pseudoacacia*), was evaluated through a fuzzy approach based on a spatially-explicit multi-criteria evaluation (MCE) approach. A specific assessment of the land suitability for two fast growing and high-productive grasses such as giant reed (*Arundo donax*) and vetiver

(*Chrysopogon zizanioides*), was also performed. Land availability for these cellulosic biomass crops was evaluated by applying an economic approach based on the marginality concept (Shortall, 2013), which is suitable for predictive scopes on the future spatial allocation of these lands, with particular regard to minimize competition with food production (i.e., low profitability and high susceptibility to land abandonment). Additional land constraints (i.e., legal or topographic) were taken into account to exclude land devoted to nature conservation as well as those with restrictions to mechanization.

Fig. 1. Schematic approach to land availability for second-generation biofuel production from perennial lignocellulosic (non-food) bioenergy crops.

2. Methods

The flowchart (Fig. 2) of fuzzy measures in MCE (Lewis et al., 2015) shows a series of basic steps for assessing land suitability and availability for five lignocellulosic bioenergy crops in Italy. MCE, which expands the commonly used MCDA, was coupled with spatially-explicit analysis in a geographic information system (GIS) environment in order to evaluate land availability and potential biomass productivity of each of the five leading bioenergy crops. This minimizes competition between bioenergy and food production on the one hand, and nature conservation on the other hand.

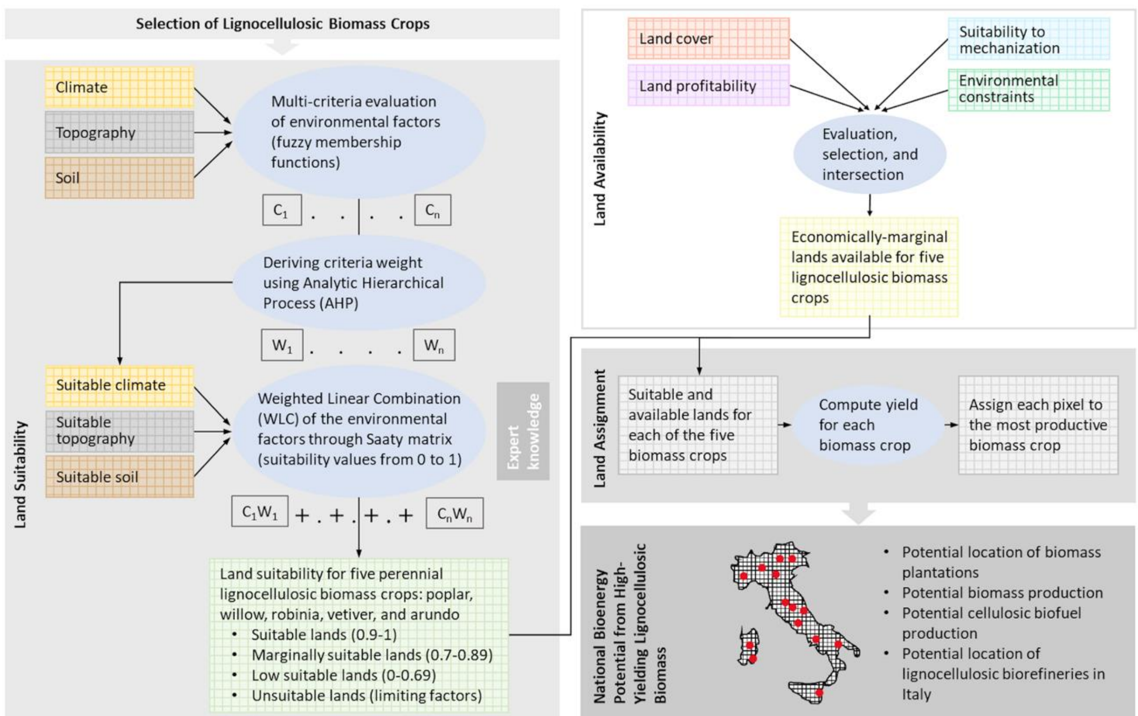

Fig. 2. Flowchart illustrating the different steps of the land availability study for sustainable lignocellulosic biomass and biofuel production, with an emphasis on selection of lignocellulosic bioenergy crops, land suitability and availability, land assignment, and potential biomass productivity.

2.1. Selection of lignocellulosic bioenergy crops

We targeted five non-food bioenergy crops, which have attracted great attention as a potential lignocellulosic feedstock for bioethanol production in Italy: poplar (*P.* ×

canadensis), willow (*S.* alba), black locust (*R. pseudoacacia*), giant reed (*A. donax*), and vetiver (*C. zizanioides*) (Fig. 3). These crops can potentially produce high-yielding lignocellulosic biomass with low input requirement and grow on marginal lands in a broad range of climate conditions, therefore avoiding direct competition for fertile farmlands with food crops. Of particular importance, interspecific, intercontinental (Europe and America) hybrid crosses between *P. nigra* and *P. deltoides* (*P.* × *canadensis*) are behind many of the commercially promising hybrids of poplar and have long been deemed important genetic materials for breeding and improvement programs for many regions, including Italy (Clifton-Brown et al., 2019).

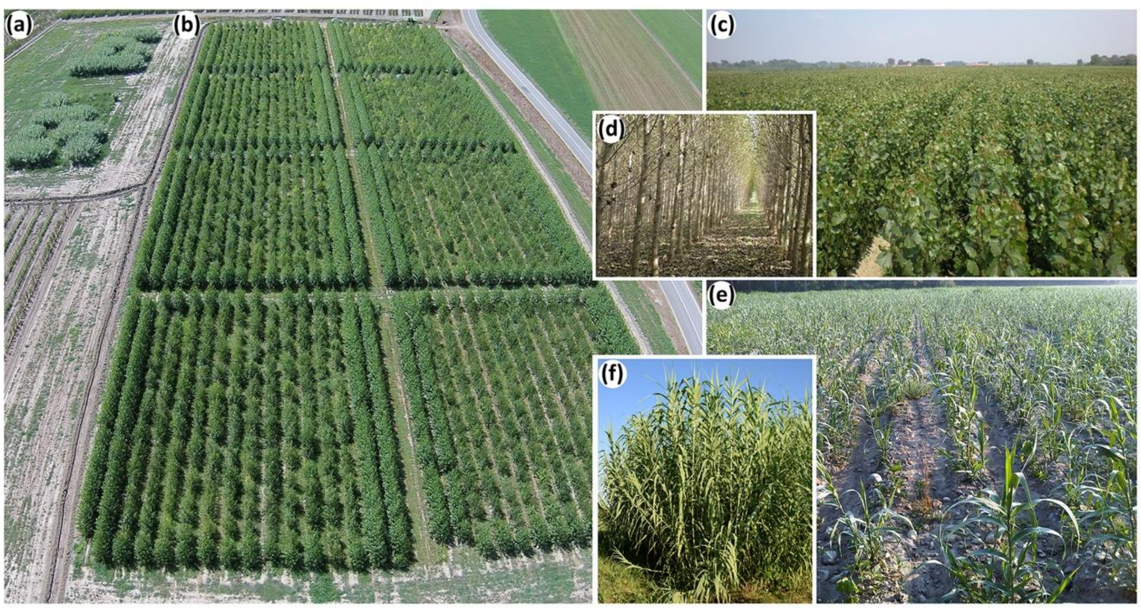

Fig. 3. Examples of potential lignocellulosic biomass crops. (a) Experimental plantations of three high production ecotypes of *Arundo donax* in Savigliano, Piedmont, Italy. (b) Experimental plantations of about 800 genotypes of a Euro-Mediterranean association population of *Populus nigra* in Savigliano, Piedmont, Italy. Photographs (a-b) are a drone aerial view of the poplar and giant reed field trials in the context of the EU-funded project

WATBIO (https://cordis.europa.eu/project/id/311929), aimed at developing lignocellulosic biomass crops suitable for growing on drought-stressed marginal lands. (c) One-year-old commercial plantation of a high production genotype of *P.* × *canadensis* in Savigliano, Piedmont, Italy. (d) Five-year-old commercial plantation of a high production genotype of *P.* × *canadensis* in Savigliano, Piedmont, Italy. (e) One-year-old stand of an *A. donax* ecotype in Savigliano, Piedmont, Italy. (f) Two-year-old commercial ecotype of *A. donax* in Savigliano, Piedmont, Italy. Photographs (c-f) are courtesy of Mr. Franco Alasia, Alasia Franco Vivai, Piedmont, Italy.

2.2. Land suitability

The identification of potentially suitable lands for lignocellulosic bioenergy crops in Italy was undertaken based on the integration and analysis of different spatially-explicit factors compiled in a GIS environment. The spatial suitability analysis was derived from the multivariate relationship between selected environmental factors and the ecological requirements of the five lignocellulosic bioenergy crops.

2.2.1 Environmental factors

Environmental factors were selected by the authors according to literature review and data availability for Italy. Climate (annual average temperature, annual mean precipitation, winter minimum temperature), topographic (distance from the seacoast, slope), and soil (soil texture, soil depth) data were considered henceforth as environmental variables.

Climate data by Blasi et al. (2007) were retrieved in accordance with the indicators proposed by Corona, Salvati, Barbati, & Chirici (2008). A linear distance algorithm was applied to the official national terrestrial borders to calculate the distance from the coastline. Slope data were derived from a national digital elevation model (DEM) with an original spatial resolution of 75-m. Whereas, soil texture and depth data were extracted from currently available databases developed at the Soil Cartography Laboratory of the Italian Council for Agricultural Research and Economics (CREA, Florence). All spatial data were then resampled into raster layers at 250-m spatial resolution.

2.2.2 Fuzzy membership functions and multi-criteria evaluation

To inform parameters and criteria selection for each step of the analysis, we conducted a literature review of studies on the mapping of land suitability and land availability associated with biofuel production. We parameterized the fuzzy membership functions and each step of the MCE, based on a literature review of the ecological characteristics of every selected crop, with all parameters finally reviewed by an independent panel of nine experts (Table A.1). The suitability assessment was based on a fuzzy MCE, where fuzzy functions were applied to score land suitability according to each environmental factor (Corona et al., 2008). The GIS-based MCE decision support module in the IDRISI Selva (v. 17.02, Clark Labs, Clark University, MA, USA) geospatial and image processing software was used to aggregate scores and generate a final suitability value for each lignocellulosic bioenergy crop at 250-m spatial resolution. Analytic hierarchical process (AHP), which is an efficient decision-making approach to examine complex problems, was applied to further determine the relative weight of each environmental factor in defining the suitability for each of the five lignocellulosic bioenergy crops in a given pixel (Saaty, 1980). Furthermore, weighted linear combination (WLC) method was employed to combine the scores of individual environmental factors (Corona et al., 2008). In addition, independent experts' opinion was used for weighting such factors in influencing land suitability through pair-wise comparison in AHP. The weights of experts were then averaged into unique values for each of the five lignocellulosic bioenergy crops (Table 1). As a result, suitability values ranging from 0 (no suitability) to 1 (complete suitability, i.e., optimum of the species) were produced through MCE for each of the five lignocellulosic bioenergy crops.

Finally, according to the classification scheme proposed by Corona et al. (2008) and adapted from FAO (1976), membership functions were assigned to each of the three linguistic variables: (i) suitable land (fuzzy value = 0.90–1.00); (ii) marginally suitable land (fuzzy value = 0.70–0.89); and (iii) low suitable land (fuzzy value = 0.00–0.69). For each of the seven environmental factors, pixels with values lying outside the range reported by the fuzzy membership functions for the lignocellulosic bioenergy crops were considered not suitable for that crop and subsequently masked (i.e., unsuitable lands).

Table 1

Weights adopted for the aggregation of the fuzzy suitability values relative to each environmental factor and each lignocellulosic bioenergy crop.

Factors	Lignocellulosic bioenergy crops				
	Chrysopogon zizanioides	*Populus × canadensis*	*Arundo donax*	*Robinia pseudoacacia*	*Salix alba*
Annual mean temperature	0.293	0.117	0.25	0.119	0.105
Annual mean rainfall	0.182	0.306	0.367	0.269	0.29
Winter minimum temperature	0.212	0.066	0.135	0.071	0.077

Distance from the seacoast	0.171	0.085	0.044	0.107	0.05
Slope	0.021	0.087	0.05	0.098	0.17
Soil depth	0.064	0.198	0.126	0.13	0.174
Soil texture	0.057	0.141	0.028	0.206	0.134

2.3. Land availability using a marginality approach

To avoid competition with food production and nature conservation, the availability of agricultural lands for lignocellulosic bioenergy crops was assessed according to Sallustio et al. (2018), after taking land profitability and environmental constraints into account (i.e., protected areas designated for nature conservation purposes). In addition, land slope was included as a third criterion because of its implication for the mechanization of agriculture. Following the proposed classification, only marginal agricultural lands were considered available for lignocellulosic bioenergy crops. Conversely, lands with slope greater than 30% (sub-marginal lands) and those having high profitability for agricultural production and/or nature conservation (supra-marginal lands), were considered not available for lignocellulosic bioenergy production. Furthermore, following a decreasing gradient of profitability, that is inversely related to the susceptibility for abandoned land, a map for marginal lands available for lignocellulosic bioenergy crops was generated. Available lands were further distinguished into three subclasses, namely low, intermediate, and high marginal agricultural lands. This conservative approach is in accordance with the current national legislation on the implementation of European Council Directives 2015/652 of 20 April 2015 and 2009/28/EC of 23 April 2009 (President of the Italian Republic, 2017), allowing the cultivation of bioenergy crops in less productive areas. Only pixels classified as agricultural lands by the Coordination of information on the environment (Corine) Land Cover (CLC2012) project (Buttner and Kosztra, 2012) were considered available.

2.4. Land assignment and potential lignocellulosic biomass feedstock availability

The map of marginal agricultural lands was overlapped with land suitability maps in a GIS environment in order to restrict the land assignment procedure to pixels classified as marginal, thus considered as available for biomass production. Only pixels having a fuzzy value ranging from 0.90 and 1.00 for a specific crop were considered as suitable, neglecting those with a decreasing level of suitability. A productivity criterion was computed to assign every pixel to only one specific crop with the highest biomass productivity potential. Thus, the five lignocellulosic bioenergy crops were ranked according to their annual dry biomass productivity determined through comprehensive review of scientific and technical literature (Table A.2). Pixels were finally assigned to the suitable crop with the highest productivity.

The average annual yield data were used to estimate potential annual biomass production on marginal lands that can be converted into cellulosic biofuels assuming a technological efficiency of 35%, and that one dry ton of lignocellulosic biomass can generate approximately 300 liters of ethanol (Hamelinck et al., 2005; Perez-Verdin et al., 2009). The focal statistics tool in ArcGIS v. 10.1 (ESRI Inc., Redlands, CA, USA) was used to estimate the potential annual biomass availability within a collection radius of 70 km from each pixel (250-m pixel size) of the Italian territory, in full compliance with the national regulations on the short-distance biomass supply (Italian Ministry of Agricultural Food and Forestry Policies, 2010).

3. Results

3.1. Land availability for lignocellulosic bioenergy crops

Maps resulting from MCE are reported in Fig. 4. Excluding *S. alba*, all species showed a relatively high suitability across Italy except over the Alpine chain, mainly due to environmental constraints. *S. alba* showed a relatively high environmental plasticity with medium-to-low suitability except over a hotspot concentrating high suitability values in northeast Italy. Similarities in the spatial distribution of suitability values are particularly visible for *P.* × *canadensis* and *R. pseudoacacia*, according to analogous environmental factors reported by their fuzzy membership functions. *C. zizanioides*, even more than *A. donax*, showed high suitability values across the whole country except over steep zones close to the mountain areas.

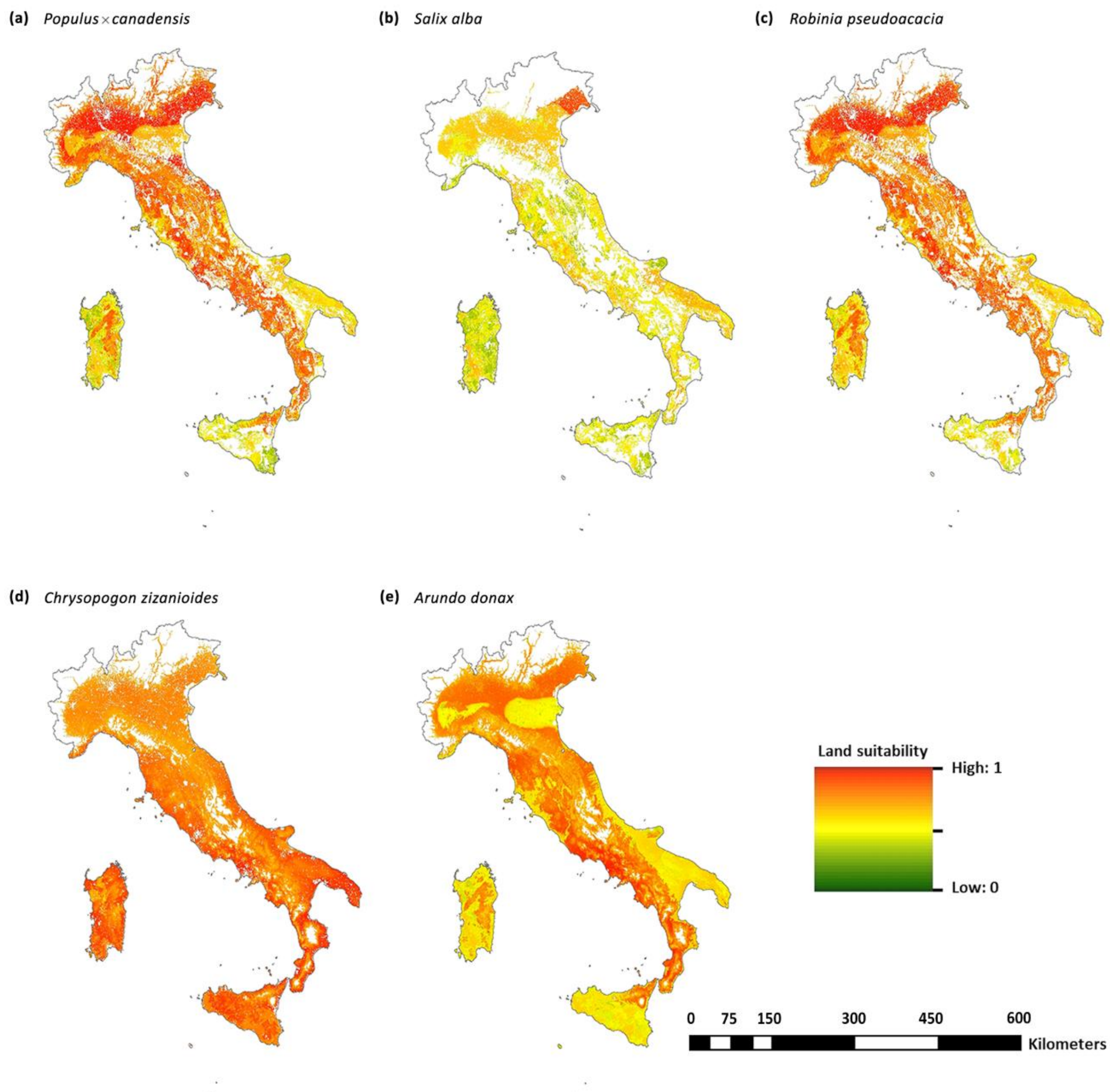

Fig. 4. Land suitability maps for five lignocellulosic bioenergy crops in Italy. (a) poplar (*Populus × canadensis*), (b) willow (*Salix alba*), (c) black locust (*Robinia pseudoacacia)*, (d) vetiver grass (*Chrysopogon zizanioides*), and (e) giant reed (*Arundo donax*). The digital values of fuzzy suitability range from 0 (low suitability) to 1 (high suitability).

Based on the marginality approach, 38.6% of agricultural lands (corresponding to 6,770,961 hectares) resulted available for lignocellulosic bioenergy crops according to different levels of marginality (Fig. 5).

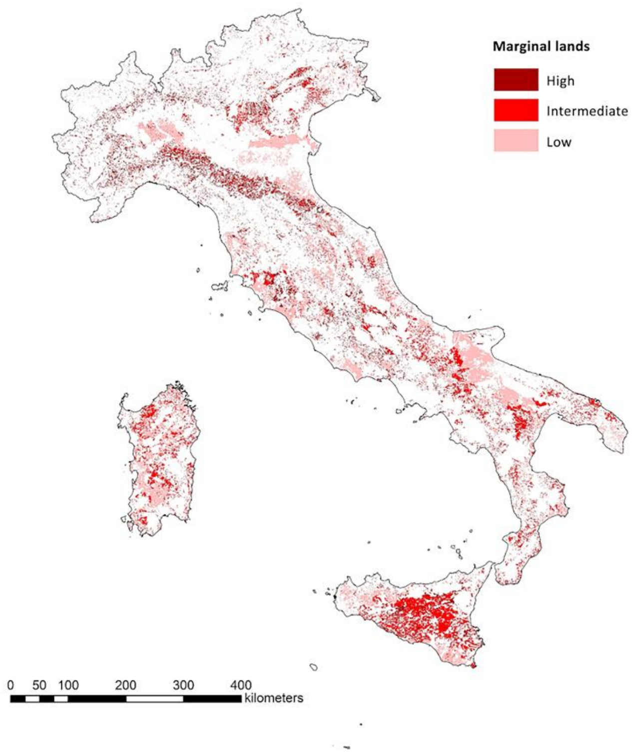

Fig. 5. Map of the spatial distribution of marginal lands available for lignocellulosic bioenergy crops in Italy ranked by their level of marginality (high, intermediate, and low).

Of these marginal pixels, 41.5% (corresponding to 2,811,064 hectares) were classified as suitable for lignocellulosic bioenergy crops (Fig. 6 and Table 2). Other 4,786,250 hectares of suitable lands fell into non-marginal lands, particularly within the so called supra-marginal lands (97%), thus highlighting the key role of land availability restrictions when developing suitability maps for cellulosic biofuels to avoid conflicts with food production (i.e., excluding high profitable lands) and nature conservation, which constitute important components of future solutions to meet national and global demands for sustainable food and rural development.

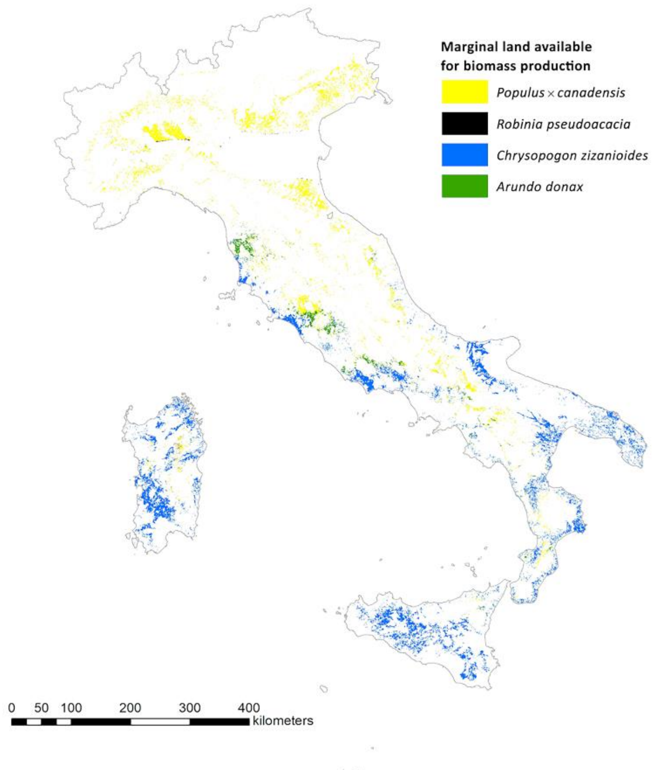

Fig. 6. Map of potential available lands assigned to each lignocellulosic bioenergy crop species in Italy.

Marginal agricultural lands suitable for lignocellulosic bioenergy crops are mostly located in low marginal lands (52.5%), followed by intermediate and highly marginal lands (31.1% and 16.4%, respectively). The proportion of lands resulted as suitable for lignocellulosic bioenergy crops is inversely related to their degree of marginality. Indeed, 46.3% of low marginal lands resulted suitable for lignocellulosic bioenergy crops against 34.2% of high marginal ones. With regard to the individual bioenergy crops, no land was assigned to *S. alba* due to overlap of its suitability map with other species, particularly *C. zizanioides* and *P.* × *canadensis*, with both having higher biomass productivity. Marginal agricultural lands were mostly dominated by *C. zizanioides* (55.7%) due to its ecological plasticity and high productivity. *P.* × *canadensis* and *A. donax* showed a relatively high contribution in terms of land assignment (36.5% and 7% of the marginal agricultural lands, respectively), while *R. pseudoacacia* only accounted for 0.8% of the marginal agricultural lands. It is worth noting that poplar currently represents the crop mainly used for bioenergy purposes in Italy (Romano and Plutino, 2018).

Table 2

Potential land area (hectare) available for lignocellulosic bioenergy crops in Italy in relation to the agricultural marginality classes.

Lignocellulosic bioenergy crops	Land available for bioenergy crops			Land not available for bioenergy crops		Total
	High marginality	Intermediate marginality	Low marginality	Submarginal	Supramarginal	
Chrysopogon zizanioides	125,253	584,923	855,721	77,942	2,000,499	3,644,337
Populus × *canadensis*	288,138	256,717	481,910	59,631	2,218,738	3,305,133
Arundo donax	46,030	26,976	122,608	7,474	383,435	586,523
Robinia pseudoacacia	2,843	5,272	14,674	68	38,464	61,320
Total	462,265	873,887	1,474,912	145,114	4,641,136	7,597,314
Total agricultural land	1,350,528	2,232,689	3,187,744	876,563	9,887,495	17,535,019

3.2. Forecast of annual lignocellulosic biomass supply and spatial distribution

Potential annual dry biomass production on the 2,811,064 hectares of marginal lands in Italy amounts to 91,654,538 megagrams per year (Mg yr^{-1}). Considering the biomass to biofuel technological efficiency (see section 2.3), this value could produce 27.5 billion liters of bioethanol corresponding to 463.3 million gigajoules. A large part (82%) of such production would come from vetiver plantations, followed by poplar and giant reed (12.2% and 5.5%, respectively), with a marginal contribution from other crops such as black locust (0.3%). This production would fulfill 69.1% of the national liquid transportation fuel consumption in 2018 (i.e., 44.4 billion liters; (Italian Ministry of Economic Development, 2020)) thus having a strong impact on the national energy sector, and great implications in terms of related GHG emissions (Table 3). If we restrict this evaluation to only high marginal lands (462,265 hectares), biomass production would be 10.4 million Mg yr^{-1}, that can be converted into 3.1 billion liters of cellulosic ethanol, fulfilling only 7.8% of the current national liquid transportation fuel consumption.

Table 3

Potential biomass yield and cellulosic ethanol production on Italian marginal agricultural lands and their relative contribution to the national liquid fuel consumption.

Lignocellulosic bioenergy crops	Potential biomass yield (Mg dry mass year^{-1})	Potential cellulosic ethanol production (billion liters year^{-1})	Percentage contribution to liquid transportation fuel consumption in Italy
Arundo donax	5,105,124	1.5	3.8%
Chrysopogon zizanioides	75,163,026	22.6	56.6%
Populus × canadensis	11,147,964	3.3	8.4%
Robinia pseudoacacia	238,425	0.1	0.2%
Total	91,654,538	27.5	69.1%

4. Discussion

4.1. Cellulosic biofuel contributions to a sustainable renewable energy future in Italy

The findings presented in this study provide evidence that lignocellulosic bioenergy crops grown on marginal lands available in Italy play an essential role in achieving the targets of the revised EU's renewable energy directive. It is rather difficult to compare our results with those obtained by other studies, mainly due to the differences of marginal lands definitions, the type of land constraints adopted, the environmental and socioeconomic restrictions, and lignocellulosic bioenergy crops considered (Lewis and Kelly, 2014). Interestingly, the projection to fulfill 7.8% to 69.1% of the current national liquid transportation fuel consumption by planting lignocellulosic biofuel feedstocks on marginal lands available in Italy is consistent with that of Cai et al. (2011) estimated (from 10 to 52%) under various land use scenarios worldwide. With the rising emphasis of some major European car manufacturers to strengthen their production of electric vehicles, this projection might also increase, considering the reduction of the overall national liquid transportation fuel demand.

Considering the increasing interest in the mobilization of marginal lands for bioenergy production (Schröder et al., 2018), our results show that there is a non-negligible amount of such lands available in Italy. This might have a two-fold positive implications in: (i) fostering bioenergy production while minimizing conflicts with food production and nature conservation and while preventing indirect land-use changes (Kluts et al., 2017; Soldatos, 2015; Solinas et al., 2015); and (ii) representing a valuable option to sustain local economies and to contain land abandonment and outmigration in economically-marginal rural districts (Marchetti et al., 2014; Russi, 2008). The latter target is particularly relevant and should be taken into account within EU policies and strategies such as the ‘cohesion policy and rural development policies’ (Mantino and De Fano, 2015; Pagano and Losco, 2016) to boost economic and social innovations in rural and urban areas that are still in their infancy (Carrosio, 2016; Cesaro and Marongiu, 2017). It is also important to highlight that these social, economic, and environmental challenges are recognized among the key pillars for sustainable development in southern Europe, where Italy is currently playing a leading role within the entrepreneurial ecosystem, with the support of private investment funds (de Arano et al., 2018; Italian agency for territorial cohesion, 2016), in boosting the production of advanced liquid biofuels (Eurostat, 2016).

The current EU bioeconomy market is estimated at about € 2.4 billion, which includes, among others, agriculture, forestry, and wood-based industry. In addition, biofuels and other bio-based products are produced using about 2 billion tons of biomass (Scarlat and Dallemand, 2011). Importantly, the development trend of emerging bio-based sectors foresees a total biomass demand for 2050 of about 290–320 million tons oil equivalent (MTOE) (Schröder et al., 2018). Italy seems to have all favorable conditions for a sustainable growth of bio-based industry, including cellulosic biorefineries. Overall, the findings of this study demonstrate the real potential for mobilizing marginal lands to produce cellulosic biofuels and to contribute substantially to the national target conceived to increase by 20% the economic impact of the bioeconomy by 2030 (Italian agency for territorial cohesion, 2016). This is also in line with the smart intensification vision to unlock the potential of marginal lands in the EU (Weltin et al., 2018).

4.2. Potential lignocellulosic biomass production with perennial grasses and short rotation trees in Italy

Evaluating potential biomass production and its spatial location is extremely important to support future decisions concerning biomass provisioning and biorefineries location (Monti and Cosentino, 2015). In this regard, the spatial analysis of potential lignocellulosic biomass available within 70 km of collection radius (Fig. 7) may further contribute to the integrated development strategy of the Italian bio-based industrial sector that is currently characterized by a network of large, medium, and small-sized firms working together (Italian agency for territorial cohesion, 2016). Comparing the hotspot areas of potential biomass availability with the first of its kind commercial-scale lignocellulosic biorefinery in Europe (Crescentino, Piedmont, Italy) operated by Versalis, the chemical division of the Italian oil company Eni, a high degree of spatial overlapping was observed. In addition to Italy, a flagship H2020 EU-funded project BIOSKOH (www.bioskoh.eu) is using various lignocellulosic feedstocks in order to consolidate lignocellulosic-based biorefineries in the EU (Hassan et al., 2019). This second largest lignocellulosic biorefinery project will transform a brownfield industrial site in the Slovak Republic into a cellulosic ethanol production facility. This overlap is even more evident when considering the flagship projects promoted by the Italian Cluster of Green Chemistry (Italian agency for territorial cohesion, 2016) aimed at fostering the conversion of existent industrial sites affected by the 2008 economic crisis into green biorefineries, or other bio-based industries. This knowledge will contribute to better organizing the future biomass supply chains for cellulosic biorefineries, creating valuable partnerships with local actors, and promoting positive externalities of small-scale economies in marginal areas of the country.

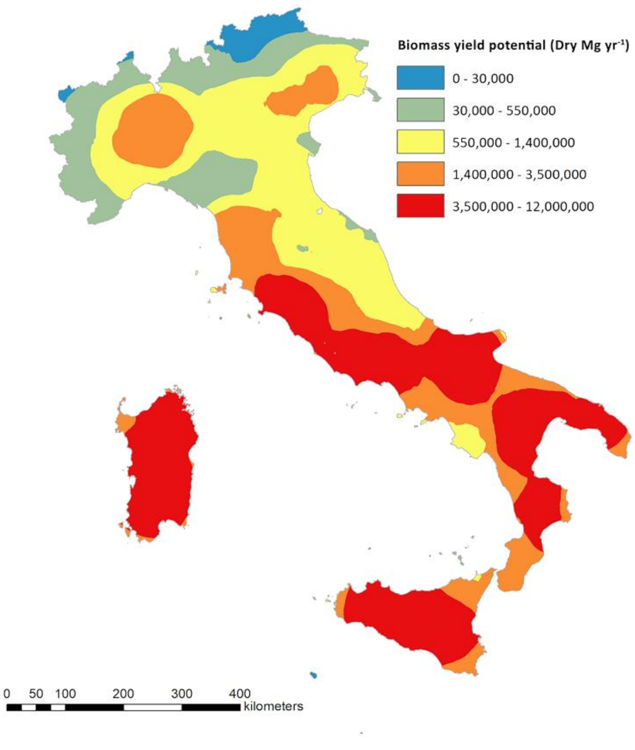

Fig. 7. Potential annual average harvestable biomass yield of lignocellulosic bioenergy crops (Mg dry matter yr^{-1}) within a collection radius of 70 km.

The availability of spatial-explicit data on potential feedstocks can help regional administrations to implement policy choices by further supporting public investments in this sector and in turn enhancing their capacity to allocate national and EU funds that often are not completely used (Carfora et al., 2017). Detecting marginal lands and assessing their suitability to produce novel and different types of goods and services that are able to strengthen local economies are crucial challenges towards their mobilization and sustainable use (Schröder et al., 2018). The impact of such novel agro-ecosystems devoted to bioenergy crops in terms of ecosystem services provisioning should be also taken into account, considering possible trade-offs as well as impacts of certification schemes in terms of sustainability (Gissi et al., 2016; Haines-Young and Potschin, 2010; Nikodinoska et al., 2018; Scarlat and Dallemand, 2011; Scorza et al., 2020; Verkerk et al., 2014).

4.3. Limitations of the study and future recommendations

There were some limitations of the study. First, it is difficult to assess the uncertainty in this kind of studies due to the amount of input data and also considering error propagation (Lewis and Kelly, 2014). However, in our study, the adoption of different thresholds for marginality in agricultural lands (i.e., from high to low marginality) and the restriction of suitable lands to only those with highest fuzzy values (fuzzy value = 0.90-1.00), can be considered as a conservative approach that allows us to limit overestimates, which can negatively affect decision-making processes. Second, additional predictors (e.g., road network, local land form, soil nutrition, and crop physiology) and/or more accurate data (i.e., regional land-use and soil maps) can be included in the methodological approach when zooming in to regional and local scale assessments; this may address local and place-based planning objectives concerns more precisely (Delivand et al., 2015; Gissi et al., 2016). This consideration is not limited to land suitability assessment but should be extended to the potential biomass production that is strictly dependent on, e.g., environmental, biological, technical, and farming aspects (Horton et al., 2021; Streich et al., 2020). Hence, it is important to remark that the approach we implemented in this study can be useful as a preliminary and exploratory analyses at large scale (i.e., country), and especially under restricted geo-spatial data availability, to support decision-making processes.

Based on the inherent limitations of the study, future research is increasingly required to focus on improvements on secondary data (both statistical and cartographic) for a more precise, spatially-explicit estimation of biofuel industry potential and land-use conflicts, considering also the economic opportunities derived from second-generation bioenergy crops (de Arano et al., 2018; Romano and Plutino, 2018). Within such strategies, the positive impact in terms of GHG emission reduction should be better clarified in light of integrated risk mitigation strategies (ISPRA, 2018). The contribution of a country-level strategy for sustainable cellulosic biofuel industry to the carbon credit market should be investigated more precisely and clarified under different socioeconomic and environmental scenarios. Similarly, scenario-based life cycle assessments should be performed to further clarify the effective contribution of cellulosic biofuels in terms of sustainability (e.g., GHG reduction), thus orienting future policy and planning strategies, particularly concerning issues of land use changes (Field et al., 2020).

The land availability maps generated in this study provide a strong foundation for further exploration of marginal land available for lignocellulosic bioenergy production in Italy; the estimates can also be integrated with research and innovation efforts in modern plant and industrial biotechnology and precision agriculture to help improve biomass feedstocks quantity and recalcitrance to processing and create sustainable standards. Historical green revolution aimed at improving crop germplasm did result in land sparing (Stevenson et al., 2013). A reinforced allocation and use of marginal lands for bioenergy crops will contribute to crop mix and biomass yield stability.

The challenges, however, are also to design multi-criteria bioenergy crop ideotypes – idealized plants that can grow in niche environments (Streich et al., 2020) that play a fundamental role in accomplishing the United Nations (UN) Sustainable Development Goals (SDGs). Considering the raising emphasis around the efficient use of water for food and energy production (D'Odorico et al., 2018), more efforts should be carried out especially on developing water-use efficient crops able to maintain biomass production in water-limited and marginal lands (Taylor et al., 2019) under various environmental conditions (Evangelistella et al., 2017; Ludovisi et al., 2017; Maesano et al., 2020; Streich et al., 2020). Other relevant breeding targets should include bioenergy crop architecture and phenology (Fabbrini et al., 2019), lignocellulose composition, and tolerance to environmental stresses to improve biomass yield and quality, as well as the stability of biomass production under marginal lands conditions (Pancaldi and Trindade, 2020). The global SDGs present a formidable challenge to scientists and society alike, highlighting the pressing need to radically rethink agriculture, given the urgency of climate and health protection. Artificial intelligence (AI) and big omics data are part of the answer. Developing high-yielding, low-input, and climate resilient biomass crops that can be grown on marginal lands for improving global energy and food security must leverage next-generation AI-augmented breeding (Harfouche et al., 2019). Coupling this with effective marginal land management strategies, intercropping and crop rotation will significantly contribute to the increased use of these lands for bioenergy crop cultivation (Qaseem and Wu, 2021).

Additionally, industrial-academic partnerships for promoting research and innovation must be implemented and strengthened to develop more profitable and sustainable cellulosic biofuel production (Youngs and Somerville, 2017). A clear need for more knowledge exchange between countries that have national programs in bioenergy through organizations like the International Energy Agency (IEA) Bioenergy is vital to ensure the sustainable development of bioenergy in a broader regional or global perspective

(Junginger et al., 2019). It is to be noted that Qaseem & Wu (2021) have rightfully advocated for the creation of a national inventory of technical and economic potential of biomass feedstocks that could be planted on marginal lands in China; this tool can be leveraged to highlight the advantages and disadvantages of using marginal lands for bioenergy production and promote effective policy design. Finally, other aspects of sustainability of bioenergy production on marginal lands not considered here, such as innovative agronomic solutions and the adoptions of certification schemes (Pulighe et al., 2019) able to maximize the sustainability of the site-specific production systems, might be readily co-managed.

5. Conclusions

Following the debate on land use for sustainable cellulosic biofuel production, we provided an estimate of marginal land availability according to different levels of economic marginality. Our results showed that planting cellulosic biofuel feedstocks on these marginal lands may fulfill 7.8–69.1% of current national liquid transportation fuel consumption, thus limiting potential land use conflicts with conventional crops without affecting areas designated for nature conservation.

Furthermore, our study highlighted the urgent need for a comprehensive bioenergy evaluation at a regional scale that encompasses: (i) a precise assessment of the availability of abandoned and marginal lands for biomass and bioenergy production; (ii) a spatially-explicit analysis of the availability of industrial sites/refineries that can be converted into biorefineries; (iii) a refined analysis of biomass availability including by-products and waste from agriculture, livestock production and local industry; and (iv) a thorough improvement in data sharing and transfer of knowledge, skills, and results of ongoing projects in a broader geographical area.

Although marginal lands have often been suggested as a solution to issues of increasing land scarcity and decreasing quality of land brought into production, as well as an ideal way to meet mounting land demands for lignocellulosic biomass production, their locations and conditions in Italy are not well known. It is also important to emphasize that the availability of marginal land tackles part of the problem but does not give a concrete way forward, hence the human (farmers, local landowners, investors, policymakers, and stakeholders) role in decisions to invest in these lands should be seriously considered. Farmers and landowners acceptance of perennial cellulosic crops in the future is critical and needs direct financial incentives. Indeed, cultivating lignocellulosic crops would provide a desirable opportunity for landowners who seek to make economic use of marginal lands (Cintas, Berndes, Englund, & Johnsson, 2021). Of particular importance are direct support schemes that could be expanded under the future EU's Common Agriculture Policy reform post-2020 to include bioenergy with direct payments for specific crops most suited to cultivation on marginal lands (Pulighe et al., 2019). Environmental policy reforms in Italy are crucial to ensure that our use of land supports the reduction of GHG emissions.

Importantly, there are other influencers that might impact marginal land availability for the cultivation and growth of these dedicated lignocellulosic bioenergy crops, including ecological impacts, environmental regulations, technological innovations, social and ethical adaptations as well as political boundaries. For example, Harfouche et al. (2021) highlighted how ethical reasoning, ethical decision-making, citizen-stakeholder participation, effective science communication, and bioethics education (Harfouche and Nakhle, 2020) should be used to guide responsible use of agricultural biotechnology for food and bioenergy production. Dedicated, diverse lignocellulosic bioenergy crops planted on marginal lands can have desirable environmental and societal outcomes and could make up a substantial proportion of sustainable future energy portfolios in Italy.

Declaration of interest

None.

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CRediT authorship contribution statement

Lorenzo Sallustio: Conceptualization, Methodology, Formal Analysis, Resources, Writing - original draft, review & editing. **Antoine L. Harfouche:** Conceptualization, Resources, Writing - review & editing. **Marco Marchetti:** Conceptualization, Funding acquisition, Review, Supervision. **Piermaria Corona:** Conceptualization, Funding acquisition, Review, Supervision. All authors have read and agreed to the published version of the manuscript.