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Biofuels from perennial energy crops on buffer strips: A win-win strategy

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A B S T R A C T

The objective of this work was to assess the environmental performances of advanced biofuels produced from perennial energy crops (miscanthus and willow) grown in bioenergy buffer strips (BBS) and compare them with the environmental performances of alternative systems providing the same function, i.e. private mobility. The growing evidence of potentially negative environmental impacts of bioenergy pathways calls for renewed efforts in identifying win-win bioenergy pathways, thus capable of mitigating climate change without worsening other environmental impacts. An holistic approach encompassing all the relevant areas of environmental concern is thus fundamental to highlight environmental trade-offs. Therefore, in this study we follow an attributional Life Cycle Assessment approach, but our analysis includes detailed modelling of biogenic carbon pools, nutrients cycles, infrastructures' impacts as well as the expansion of the system boundaries to include the fuel use. We find that the fragmented and linear configuration of the buffer strips does not affect significantly the GHG emissions of lignocellulosic ethanol for BBS compared to growing the crops in open field. Additionally, we find that ethanol from perennials grown in BBS has the potential to reduce several other environmental impacts associated to private mobility. Firstly, the cultivation of miscanthus and willow in BBS enables both the removal of nutrients from the environment and the removal of carbon from the atmosphere, through the creation of an additional terrestrial sink. Secondly, when compared to the use of fossil gasoline, bioethanol from BBS crops generates lower impacts on all other areas of environmental concern, such as resources depletion or air pollution.

We also find that cars fuelled with bioethanol form buffer strips perform even better than electric vehicles in all the impact categories analysed except for acidification and particulate matter emissions, where battery electric vehicles running on renewables perform slightly better.

We conclude that bioethanol from perennial crops grown in BBS is a good example of nature-based solution, able to reduce GHG emissions without shifting the environmental burden on other areas of environmental concern.

1. Introduction

Renewable energy (RE) can help to partially decouple the correlation between energy use and CO_2 emissions (Edenhofer et al., 2011). As well as having a large potential to mitigate climate change, RE can provide wider benefits. RE may, if implemented properly, contribute to social and economic development, energy access, a secure energy supply, and reducing negative impacts on the environment and health (Edenhofer et al., 2011). On the other hand, some renewables technologies can also show negative environmental trade-offs, for instance resulting in GHG emissions higher than the fossil fuels they are supposed to compete with, and, especially for biomass based energy, there may be trade-offs with other areas of environmental concern (Agostini et al., 2015; Giuntoli et al., 2015; Heck et al., 2018; IPCC, 2019), which are not always properly identified and communicated to policy makers (Agostini et al., 2020).

The anthropogenic disruption of biochemical flows (the nutrient

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Abbreviations in alphabetical order

AGB	Above Ground Biomass
BBS	Bioenergy Buffer Strips
BEV REN	Battery Electric Vehicles running on renewable electricity
BEV	Battery Electric Vehicles running on the IT electricity mix
BGB	Below Ground Biomass
CAP	Common Agricultural Policy
ES	Ecocsystem Services
GAS	Conventional ICE vehicle running on fossil gasoline
ICE	Internal Combustion Engine
M BBS BE	Miscanthus in buffer strips with border effect
M BBS	Miscanthus in buffer strips
M OF	Miscanthus in open field
N	Nitrogen
OF	Open Field
RE	Renewable Energy
SOC	Soil Organic Carbon
tot	total
vkm	vehicle kilometer
W BBS BE	Willow in buffer strips with border effect
W BBS	Willow in buffer strips
W OF	Willow in open field

cycles, both nitrogen and phosphorus), are among the environmental aspects that threat the inhabitability of the planet. Human activities now convert more atmospheric nitrogen into reactive forms than all of the Earth's terrestrial processes combined, and much of it ends up in aquatic systems. (Steffen et al., 2015). In order to limit these phenomena, under the current European common agricultural policy (CAP), the so-called cross-compliance mechanism establishes a set of standards to preserve good agricultural and environmental condition of land, which is compulsory for farmers receiving CAP payments. These standards include the protection and management of water through the establishment of buffer strips along water courses (European Commission, 2019). Buffer strips are linear landscape elements placed in between arable field margins and watercourses to capture the excess nutrients, and are established as one of the most effective potential countermeasures to fight eutrophication, (Ferrarini et al, 2017a, 2017b; Fortier et al., 2013; Mayer et al., 2007; Meehan et al., 2013; Stutter and Richards, 2012; Styles et al., 2016). In Italy the establishment of buffer strips along water courses has been mandatory since 2011 (MIPAAF, 2011).

In 2018, the European Union has agreed on a set of ambitious targets in its 2030 energy union strategy, including a measure establishing that member states must require fuel suppliers to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy (European Union, 2018). Italy expects to reach a 21.6% penetration of renewables in the transport sector by 2030 (Ministero Dello Sviluppo Economico, 2019), of which 2% is planned to derive from advanced biofuels other than biomethane (Ministero Dello Sviluppo Economico, 2019).

Bioenergy Buffer Strips (henceforth 'BBS'), i.e. perennial herbaceous or woody crops, grown in buffer strips, which can be used for energy conversion, have been proposed by several authors (Ferrarini et al, 2017a, 2017b; Gopalakrishnan et al., 2012; Ssegane et al., 2016) as a possible solution to contribute simultaneously to the production of advanced biofuels and to the reduction of eutrophication. Ferrarini et al. (2017a) have recently carried out a systematic review to assess the potential impact of BBS on multiple ecosystem services (ES) provision. They highlighted that the implementation of BBS on previous croplands, rather than on grasslands, sustains long-term provision of multiple ES such as regulation of climate, water conditions, and soil quality and protection of habitats. In particular, herbaceous buffers are more effective than woody buffers in the provision of multiple ES. Ferrarini et al. (2017a) also pointed out that the limited operating space for farm machinery might constitute an important shortcoming for cultivating bioenergy buffers compared to large-scale bioenergy plantations in agricultural land (hereafter called open field, OF). Especially, the intra- and inter-farm spatial fragmentation of biomass supply areas may increase environmental costs related to biomass collection and transport operations. However, these aspects have not yet been fully studied.

To date, several studies have assessed the various environmental impacts of buffer strips on: soil organic carbon accumulation (Falloon et al., 2004; Fortier et al., 2013; Meehan et al., 2013; Tufekcioglu et al, 1999, 2003; Young-Mathews et al., 2010); groundwater N regulation (Balestrini et al., 2011; Gopalakrishnan et al., 2012; Gumiero et al., 2011; Haycock and Pinay, 1993; Mayer et al., 2007; Noij et al., 2012; van Beek et al., 2007; Young and Briggs, 2005; Zhou et al., 2010); N_2O and other GHG emissions (Bradley et al., 2011; Gopalakrishnan et al., 2012; Meehan et al., 2013; Styles et al., 2016). However, no cradle to grave, comprehensive assessment of the environmental impacts of advanced biofuels from BBS is available. This work aims at filling this gap with a comprehensive and holistic analysis of the environmental impacts of advanced biofuels production from BBS with a cradle to grave life cycle assessment approach. We build a comprehensive life cycle inventory for the cultivation of two perennial species, Miscanthus and Willow, upon a decade of primary field data collection and applied research carried out in the Po valley by several authors on multi-species long-term field trials on biomass crops cultivated in marginal land and buffer strips (Amaducci et al., 2017; Chimento et al., 2016; Chimento and Amaducci, 2015; Ferrarini et al., 2017a, 2017b).

The hypothesis formulated is that the cultivation of bioenergy crops for biofuels production in buffer strips is a win-win option as it improves the local environmental conditions while reducing GHG emissions in comparison to other private mobility alternatives.

In this work a Life Cycle Assessment (LCA) is performed according to the recommendations of the International Standardization Organisation for LCA (ISO, 2006a; 2006b). The research is therefore organised, accordingly, in 4 phases: goal and scope definition (section 2.2), Life Cycle inventory (section 2.3), Life Cycle Impact Assessment (section 3), Interpretation (sections 4 and 5). A research design diagram is provided in Fig. 1.

2. Materials and methods

2.1. General description of the systems modelled

The modelled feedstocks are miscanthus (*Miscanthus x giganteus*, Greef et Deuter, 1983, Fig. 2a) and willow (*Salix* spp. L, Fig. 2b).

Miscanthus is a rhizomatous tall C4 grass characterized by high photosynthetic efficiency with tolerance to temperate climates (Clifton-brown et al., 2004). Miscanthus (Miscanthus x giganteus L.) has an high water, nitrogen, energy and land use efficiency

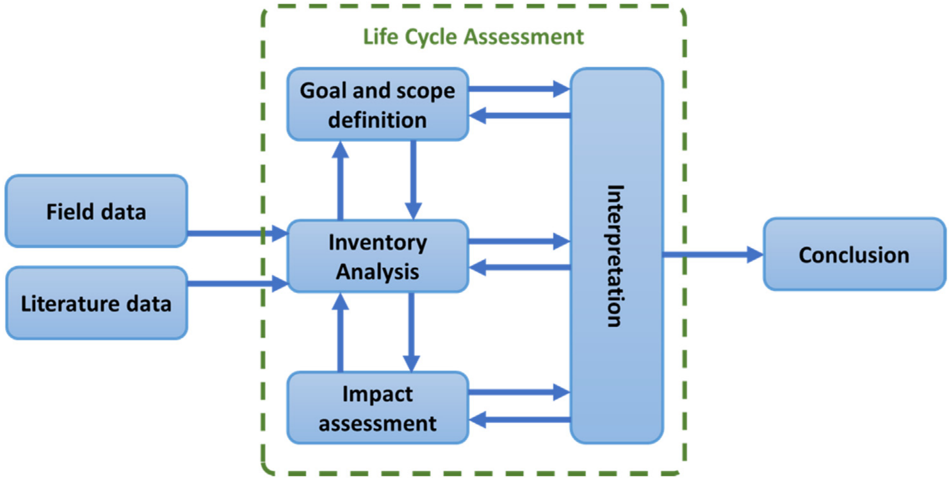

Fig. 1. Research flow diagram. The research was performed according to the International Recommendations on LCA.

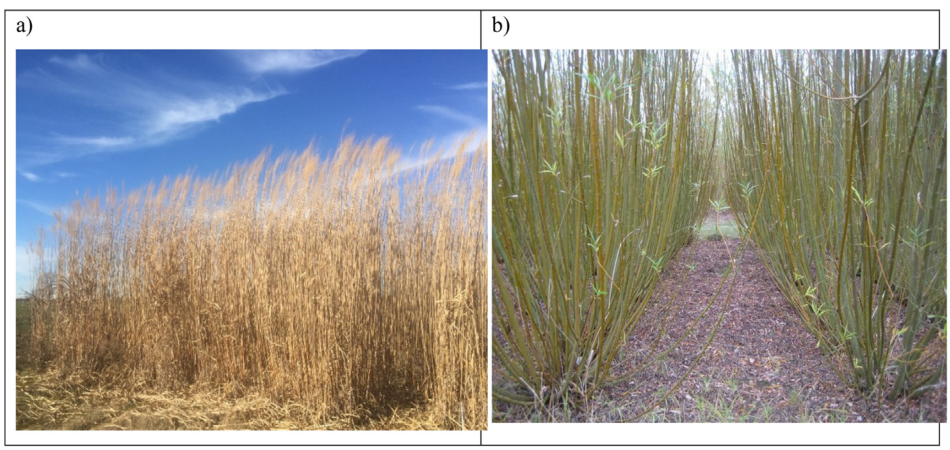

Fig. 2. Experimental bioenergy buffers plot of a) mischantus (Miscanthus x giganteus L.) and b) SRC willow (Salix spp L.).

(Lewandowski et al., 2000; Lewandowski and Schmidt, 2006), and grows in marginal conditions with a low input request (Lewandowski et al., 2016). Miscanthus rhizomes are transplanted after typical soil preparation (ploughing and harrowing). The first-year production is chopped and left in the field due to low productivity, then an annual harvest takes place till year 20, the expected end of the lifetime of the plantation.

Willow has high potentials for biomass production in BBS, thanks to its high yield potential, ease of vegetative propagation, broad genetic base, short breeding cycle, and the ability to resprout after multiple harvests (Aylott et al., 2008). The soil preparation is the same of miscanthus, then willow stems cuttings are planted. The harvest takes places every 2 or 3 years.

The cultivation of the same feedstocks in OF is modelled with the same agricultural practices as for BBS but with additional operations of weeding and fertilisation (agricultural practices not allowed in buffer strips). All details of crop management are provided in the life cycle inventory (section 2.3).

Border effect is defined as the difference in the biomass production performance between external plants and internal plants in a plot. Plants on the border of the plot usually show the highest yield, because they receive a larger amount of light, water and nutrients in buffer strips because of their linear configuration and the nutrients and water flows provided by the adjacent annual crops (Ghaley and Porter, 2014; Wang et al., 2013). The potential benefits of the border effect are included in our analysis through the definition of two additional systems with higher yields.

As recommended by Agostini et al. (2019); Koponen et al. (2018); Soimakallio et al. (2015), we include in our assessment a reference use for the land that is cultivated for bioenergy feedstocks. We assume the cultivation of both the BBS and OF takes place on former agricultural land used for annual crops rotation. In the case of BBS there is no competition with food/feed production as the production of food/feed is not allowed in BBS (no ploughing, fertilisation, pest control). The cultivation of the bioenergy perennial crops in OF is assumed to take place on land which would otherwise be abandoned. In Italy a non-negligible share (i.e. about 1% between 2010 and 2013) of agricultural land is abandoned every year (ISTAT, 2017); the additional land cultivated with perennials energy crops can thus be considered as ‘marginal’ i.e. land that would not be otherwise used for food or feed production, because less fertile or degraded, but would be left for natural regeneration of local species. Therefore, the reference land use for the calculation of biogenic carbon emissions is assumed to be natural regeneration with local grasses species. We recognize this is a key assumption of the study, nonetheless, we reckon this assumption to be representative of the Italian situation for the following reasons: i) the short timeframe of the analysis (20 years); ii) the assumption of low fertility of the land, iii) the likely occasional grazing or mowing to ensure the basic maintenance of the crop field. The latter commonly takes place not only in the interest of the owner, which otherwise would face additional costs for the reconversion of the land to arable if large bushes or trees take over grasses in the revegetation, but also because maintenance is mandatory in most Italian municipalities for wild fire prevention and landscape care. Additionally, the same type of land was investigated in Amaducci et al. (2017) and Ferrarini et al. (2020), and it is thus consistent with the data used in this study.

We calculated the average C storage based ob Soil Organic Carbon (SOC), Above Ground Biomass (AGB) and Below Ground Biomass (BGB) in all three systems (BBS, OF, natural grass between $y = 0$ and $y = 20$) and then we annualised the results in a 20 year timeframe. With this approach the results are representative both of the average of a single bioenergy crops plot in 20 years, or a mosaic of bioenergy crop fields composed of 20 equal shares of plots ages.

As defined above, the natural regeneration of grassland represents the baseline, i.e. the business as usual development of land without any production of the functional unit. It is therefore considered as an attribute of the biofuel system analysed, which replaces the abandoned land or the buffer strip to perennial energy crops causing the differences in land use related carbon storage. The results of this study should thus be interpreted as conditional to this system definition.

The biofuel systems modelled are therefore the following:

- Miscanthus in buffer strips (M BBS)
- Miscanthus in open field (M OF)
- Miscanthus in buffer strips with border effect (M BBS BE)
- Willow in buffer strips (W BBS)
- Willow in open field (W OF)
- Willow in buffer strips with border effect (W BBS BE)

The function of the systems modelled is assumed to be the satisfaction of private mobility demand.

The biomass produced in BBS or OF is processed via simultaneous saccharification and fermentation into ethanol to be used as fuel in internal combustion engine (ICE) passenger car.

To understand the significance of the environmental impacts of the biofuel systems modelled, the full life cycle, till the fuel combustion in an ICE car, is calculated and the results are compared with the following systems providing the same function, namely:

- Battery Electric Vehicles running on the IT electricity mix (BEV)
- Battery Electric Vehicles running on renewable electricity (BEV REN)
- Conventional ICE vehicle running on fossil gasoline (GAS)

The ratio behind the choice of the alternative systems lays in the current and expected future sales of private cars, with diesel cars being replaced by gasoline cars (ACEA, n.d.) and an expected large penetration of electric vehicles in the near future (European Commission, n.d.).

2.2. Goal and scope definition

The goal of this work is to assess the environmental performances of advanced biofuel production from BBS and compare them with the environmental performances of alternative systems providing the same function, i.e. private mobility. The analysis is comparative attributional and complies with international standards and recommendations (European Commission, 2011; Fazio et al., 2018; Hauschild et al., 2011; ISO, 2006a, 2006b).

The analysis is built upon three levels. In the first level, only supply chain emissions are considered. The goal is to evaluate the impact of land fragmentation in the BBS spatial configuration in comparison to conventional feedstock cultivation in OF. The functional unit is the production of 1 MJ of fuel while the environmental impact category analysed is GHG emissions.

In the second level, the functional unit does not change, 1 MJ of fuel, but the biogenic carbon emissions are included in the analysis and the environmental impact categories analysed are expanded to include all the following:

- Climate change
- Acidification
- Freshwater and Marine eutrophication
- Respiratory inorganic
- Photochemical ozone formation
- Resources use, mineral and metals
- Resources use, energy carriers

The impact assessment methods were chosen according to the International Life Cycle Data System recommended methods for Environmental Footprint Programme (Fazio et al., 2018) as reported in the Supplementary Material (Table SM1). However, we excluded some of the impact categories suggested either because the impact assessment methods are still immature (i.e. the methods for toxicity assessment are at level III, recommended, but to be applied with caution in Fazio et al. (2018)) and/or because considered less relevant and significant for biofuel pathways (e.g. ozone depletion, which depends mostly on chlorofluorocarbons emissions). The impact categories assessed are in line with the results of the analysis on the relevance of environmental impact categories choice for perennial biomass production published by Wagner and Lewandowski (2017). The goal of this level is evaluating the environmental performances of biofuel production in BBS in comparison to OF with a comprehensive approach that captures all impacts of the supply chain.

In the third level of the analysis, the goal is to evaluate the environmental performances of biofuels produced in BBS or OF in comparison to other sources of energy for private mobility (BEV, BEV REN, GAS). The functional unit is therefore set at 1 km run by a medium size vehicle (1 vkm). The environmental impact categories analysed are the same as in the second level of analysis.

For all the systems additional impacts related to ecosystems services (ES), for which quantitative methods are not available or fully developed, are discussed qualitatively.

Fig. 3 shows the relationship between the environment, the technosphere, and the three levels of the analysis carried out.

About the geographical scope, the cultivation systems are located in the Po Valley, Italy. The timeframe of the analysis is 20 years, which corresponds to both the expected duration of the BBS plantations and the average life span of a biofuel production plant, and it is reflected also in the timeframe used in annualising the GHG emissions deriving from land use change by IPCC (IPCC, 2006) and the European Commission (European Union, 2018).

The study was carried out using the software GABI ts (Thinkstep, 2019). Background data and data for the alternative systems are from Ecoinvent (2016).

2.3. Life cycle inventory

2.3.1. Supply chain emissions

To answer the question set in the goal of the first level of analysis, we modelled in detail the distance driven and fuel consumption for BBS feedstocks produced in the buffer strips of a specific municipality in Italy, San Pietro in Cerro, in the Po Valley

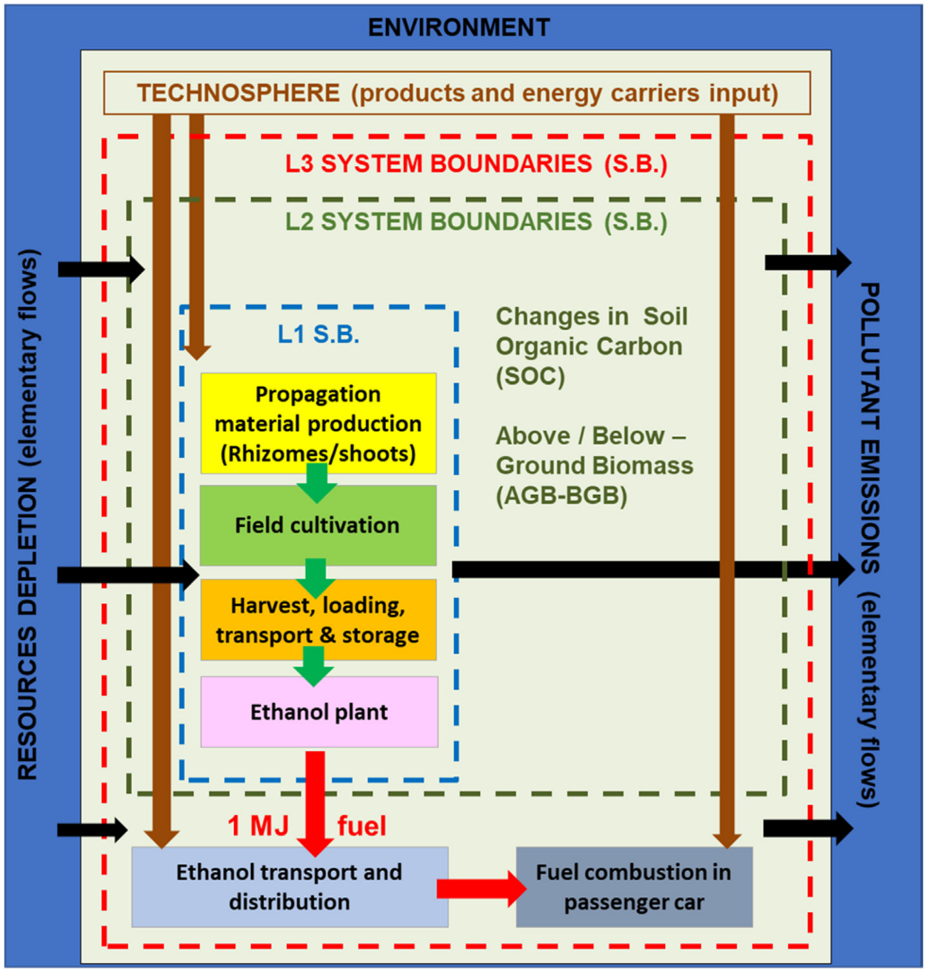

Fig. 3. System boundaries description and the three levels of analysis adopted.

(Fig. 4a). The municipality is not meant to represent an average, but rather a potential realistic case study.

With the support of a geographic information system, the rivers and water streams were geolocated and mapped, together with the agricultural land cultivated with annual crops (Fig. 4b) and then the potential buffer strips were identified (Fig. 4c). The roads and paths potentially used to reach the buffer strips were identified and measured (Fig. 4d) while for the cultivation of the open field a distance farm-field of 1.5 km was assumed.

Yearly biomass production data for miscanthus and willow were collected in a multispecies field trial established in April 2007 in the Po Valley, at Gariga di Podenzano, Piacenza province, Italy (44°58048″N, 9°41009″E). For agronomic details see in Amaducci et al. (2017). The yield data were integrated with the data from 2015 to 2017 (measured with the same method as in Amaducci et al. (2017) to obtain a production dataset of 11 years. To reach the 20 years expected life span of the plantation the remaining 9 years were assumed to have yields equal to the average of the first 11 years (Alexopoulou et al., 2015) (see Figure SM2 in the supplementary materials). This assumption is reasonable as Miscanthus yield stabilises after a peak of production at y = 4–6 (Arundale et al., 2014) and willow is rather stable for all the duration of the cultivation then start to drop around the year 20 (González-García et al., 2012).

The yields in BBS BE are assumed higher than in open field scenario as a consequence of the border effect discussed in the previous section. The border effect was estimated to result in a 32% additional biomass production according to the data from Ferrarini et al. (2017a) where the biomass yield on BBS are presented on a plant row basis for 5- and 10-m wide buffer strips. The description of the border effect calculation is reported in section 3 of the SM. Given the uncertainty and scarcity of literature on the magnitude of the border effect, we have also simulated BBS with the same yield of. Soil preparation is the same for miscanthus and willow, with ploughing and arrowing (both rotary and disk arrow) operations.

In BBS weeding and fertilisation are not allowed (MIPAAF, 2011). In OF weeding takes place once at y = 0 for willow and twice at y = 0 and once per year till y = 5 for miscanthus to control annual meadow-grass and broad-leaved weeds until leaf litter layers start acting as barrier to weed emergence. Fertilisation of miscanthus in OF is done with 60 kg N y^{-1} from y = 0 to y = 5 since early establishment will benefit from this fertilization regime (McCalmont et al., 2017; Monti et al., 2019).

Willow is fertilized with 100 kg N at y = 0 and after every harvest. Details on the agricultural practices and their timing is provided in table SM4 of the supplementary material. Miscanthus was planted with a density of 40000 rhizomes per ha while willow with 6700 shoots per ha. Both planting densities are higher than those commonly used in OF conditions since in BBS they are cultivated with the main target to function against nonpoint source agricultural pollutants. Data on environmental impacts from the production of miscanthus rhizomes and willow cuttings are taken

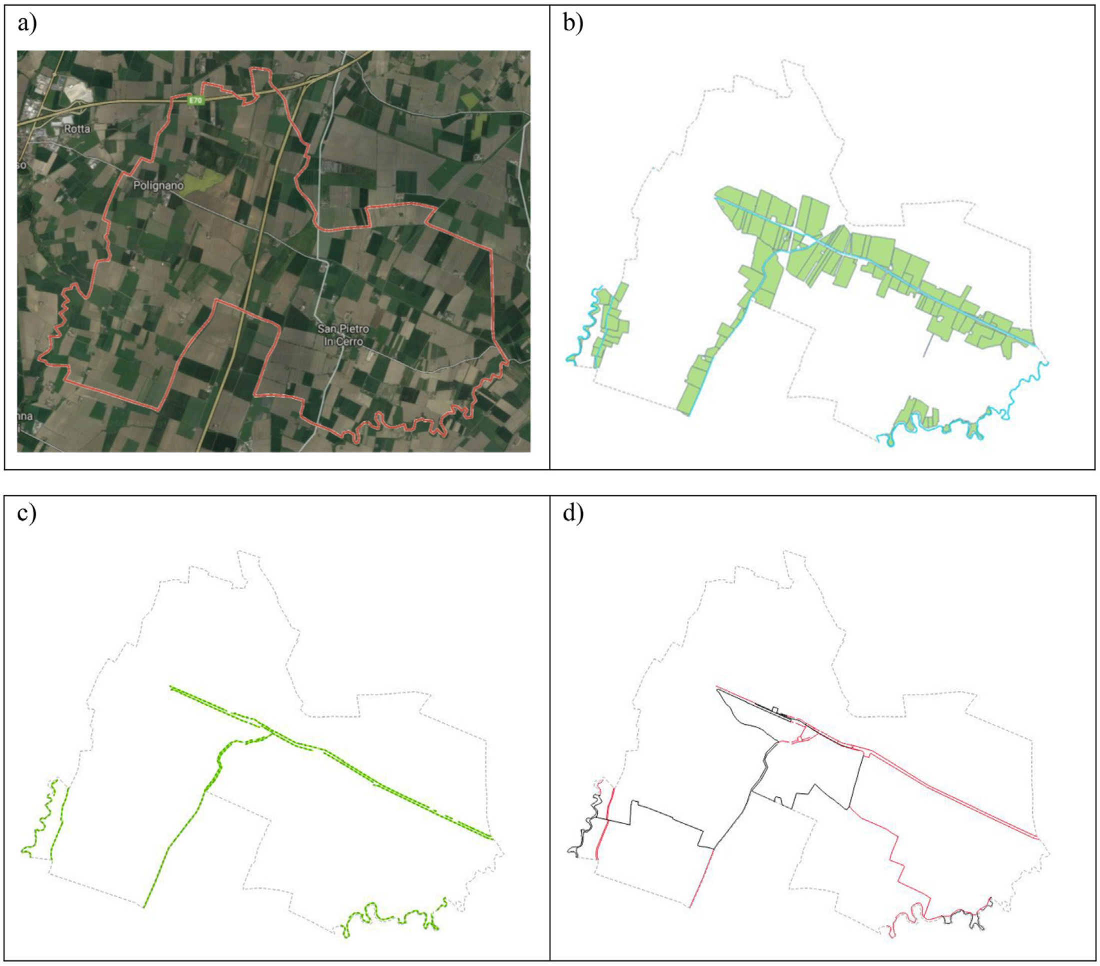

Fig. 4. a) aerial view of the municipality investigated; b) crop fields and water streams; c) potential buffer strips; d) road network.

from ecoinvent.

Miscanthus is harvested using common field practices and machinery used for fodder crops, i.e.: cutting, shredding, and baling. Square bales (about 300 kg each, moisture content of 33.6%, LHV = 17.8 MJ kg^{-1}, further details in Amaducci et al. (2017)) are collected and transported to the farm for storage. The fuel consumption for miscanthus harvesting is calculated according to Mathanker and Hansen (2015) in relation to the yield.

Willow is harvested with a cycle of 2 years (3 years only between 2010 and 2013) and is collected using a self-propelled combined forage harvester producing chips which are directly loaded on a tractor and dumper and offloaded at the farm (moisture content is 35%, LHV = 18.8 MJ kg^{-1}, further details in Amaducci et al. (2017)). Fuel consumption is proportional to the yield and it is based on the work of Bacenetti et al. (2016).

The diesel consumption of tractors and machineries for the other agricultural practices is calculated according to Fröba and Funk (2004) taking into account the power of tractors, the specific fuel consumption, and working time. A description of the method is reported in section 5 of the supplementary material.

Biomass losses due to bacterial aerobic degradation during storage of wood chips and bales and handling losses are included in the analysis, details are reported in section 6 of the supplementary material. We assume the degradation to result in CO_2 emissions only due to aerobic conditions. The bales and wood chips are then transported by truck to the ethanol plant, assumed to be at 70 km from the farm.

The ethanol plant performs simultaneous saccharification and fermentation after steam explosion of the biomass received, with on-site enzymes production and waste water stream valorisation via biogas production. The inventory for this process is taken from ecoinvent (Jungbluth and Chudacoff, 2007), but adjusted to reflect recent improvement in the process by adopting ethanol and electricity yields adopted by the European Commission in its definition of input data to assess GHG default emissions from biofuels in EU legislation (Edwards et al., 2017) The multifunctionality of the ethanol plant, which produces also excess electricity sold to the grid, was solved by attributing electricity credits equivalent to the Italian electricity mix. Further details are available in section 7 of the supplementary material.

Impacts associated to all the infrastructures are included in the analysis: tractors, machinery, sheds, ethanol plant, further details are provided in section 5 of the SM.

2.3.2. Environmental impacts including biogenic carbon and nutrients

The soil organic carbon (SOC) accumulation for the land use change from crop land to perennial crops is built from the data measured in the same field trials by Chimento and Amaducci (2015) at y = 6 (Ferrarini et al., 2020), at y = 9 and (Martani et al., 2020) at y = 11.

The amount of BGB, including roots and rhizomes for miscanthus, and roots and stools for willow, are measured in the same field trials at y = 11 (Martani et al., 2020).

The average amount of biomass in the field litter is calculated from Richter et al. (2015) for miscanthus, and (Pacaldo et al., 2013) for willow. AGB is calculated proportional to the yield (adjusted to account for the harvest losses) and the time spent in the field by the biomass: we assume a linear growth March–October then stable amount of biomass till March next year, we therefore use a C permanence correction factor of 0.75 for miscanthus and 0.75 only for the last year for willow, further details are provided in SM section 6. An additional carbon pool including the wood chips and bales is considered to store the carbon out of the atmosphere for half a year as the feedstocks are harvested once per year and consumed in one year, therefore the average permanence of carbon is 6 months.

The amount of SOC stored by the alternative use of land in OF with natural grassland or set-aside field margins in buffers trips is assumed equal to the transition from arable land to miscanthus (Falloon et al., 2004; Gosling et al., 2017; King et al., 2004). BGB for this land use transition is derived from Ferrarini et al. (2017a) and AGB is calculated by applying a root/shoot ratio of 4.6 (Peichl et al., 2012; Qi et al., 2019).

Nitrous oxide emissions (N_2O) are assumed to be the same for the energy crops and the natural species as these depend mostly on the nitrogen available, water saturation and aerobic conditions (Hill, 2019) therefore they are excluded from the analysis. Only the additional N_2O emissions deriving from the use of mineral fertilisers were considered. According to Perego et al. (2016) in the same geographical area under study, 2.1% of the N fertiliser applied is emitted as N_2O, while 15% is emitted as NH_3 (Nemecek et al., 2016).

As regards the nutrient cycles, we allocated negative emissions to the energy crops as the P and N harvested with the biomass are removed from the environment, and we consider this aspect to be additional compared to the reference system of natural grassland, thus reducing the impacts on eutrophication.

A detailed inventory containing all the input values used for the nutrients and carbon modelling is reported in section 6 of the supplementary material.

2.3.3. Fuel use and alternative systems

To enable the comparison of the biofuel produced with the alternative transportation systems, the ethanol produced is assumed to be combusted in passenger ICE cars and the fossil alternative considered is the gasoline euro 5 passenger car (GAS) as described in Simons (2016) running on EU average gasoline. The characteristics and performances of the passenger car are those of the medium size, euro 5, ecoinvent 3 passenger car (Simons, 2016). The ethanol is assumed to guarantee the same performances of a gasoline car based on the energy content of the fuel (i.e. 1 MJ ethanol = 1 MJ gasoline) as reported in Huss et al. (2013). The manufacture and maintenance of the car, and its end of life processing are included in the analysis. Beside tailpipe emissions, non-exhaust emissions, differentiated between brake, tyre, road surface abrasion or fuel evaporation are included as well (Simons, 2016).

The other two alternatives are battery electric vehicles (BEV) running on the Italian average electricity mix (BEV) or on photovoltaics (BEV REN). The BEV is described in Del Duce et al. (2016) and, as the ICE passenger car, it includes non-exhaust emissions, manufacturing and end-of-life. The BEV is supposed to represent the current alternative, while the BEV REN is meant to represent a reasonable future alternative choice considering that in 2030 the penetration of renewables in the power sector is expected to be at 55.4% in Italy (Ministero Dello Sviluppo Economico, 2019), while the second generation biofuel commercial production is still in its infancy (Hassan et al., 2019).

3. Results: Life Cycle Impact Assessment

The results of the study are presented for the three level of analysis. These results are not meant to represent the actual impacts of large-scale deployment of bioenergy production in BBS or OF, but rather to contribute to the understanding of the relevance and relative contribution of the processes involved in biofuel production and the potential trade-offs among different areas of environmental concern. The results, being modelled as the average of the life span of the systems modelled, rather than explicitly in time, can be read also as the average results of a mosaic of agricultural land plots with different ages.

3.1. Supply chain emissions: first level

At this level of analysis, only the GHG emissions of the system modelled are evaluated. These results, being very limited in scope, should be intended to contribute to the identification of hot spots and potential measures aiming at reducing GHG emissions along the supply chain of the biofuel produced (Agostini et al., 2020). The net GHG emissions range between 11 and 17.4 g CO_2 eq MJ^{-1} for all the biofuels considered.

In all systems the ethanol plant is the major source of GHG emissions, with the highest contribution from the process chemicals, internal combustion processes and enzymes nutrients (Fig. 5). For biomass cultivated in BBS, the second and third largest contribution is from diesel consumption for harvest and transport to the

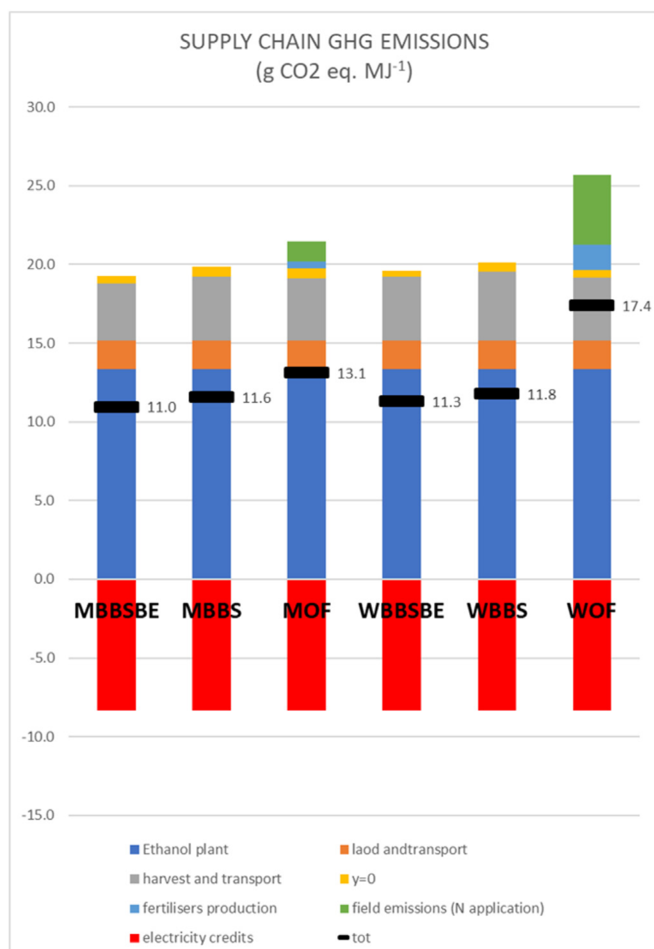

Fig. 5. Supply chain GHG emissions.

farm and loading and transport from the farm to the ethanol plant, with very limited differences between the BBS and BBS BE because most of the processes are proportional to the yield while the installation of the plantation (t = 0) provides a limited contribution.

Different results are obtained for OF, where fertilizers production and application (‘field emissions’ in Fig. 5) are responsible for emissions higher than all the harvest and transport related emissions for willow, while for miscanthus they are similar to the emissions from the transport from the farm to the ethanol plant, this is due to higher level of fertilisation for willow than for miscanthus (900 and 300 kg of Neq respectively in 20 years).

3.2. Environmental impacts of bioethanol production: second level

3.2.1. GHG emissions

As shown in Fig. 6, all the systems show negative emission of GHGs, with the mitigation ranging from −31.1 to −42.5 g CO_2 eq MJ^{-1}. The largest contribution to negative GHG emissions is provided by SOC accumulation. However, as we assumed the SOC accumulation of the alternative use of land is similar to miscanthus, these are practically cancelled out by the missed SOC accumulation of natural vegetation both in BBS and OF. The positive emissions, as shown in Fig. 5, are about 20 g CO_2 eq MJ^{-1} for all systems.

What makes the emissions negative is the larger amount of AGB and BGB and the subsequent increased C-sequestration in the biofuel systems. The total average carbon stored in roots, rhizomes, litter, bales and AGB of miscanthus is about 55 g CO_2 eq MJ^{-1} while the carbon stored in roots, stools, litter, chips and AGB of willow is about 60 g CO_2 eq MJ^{-1}. Willow has a lower amount of carbon stored below ground (in roots and stools) compared to miscanthus, however, it shows a higher total C storage thanks to the longer permanence of the carbon in the AGB, as willow is not harvested every year, and the larger amount of litter. The amount of carbon stored in AGB and BGB in natural buffer strips or open fields would amount to about 2 g CO_2 eq MJ^{-1}.

Willow shows smaller negative emissions because of the lower SOC accumulation compared to miscanthus, and therefore also lower than the natural vegetation, and the lower productivity of ethanol, resulting in higher emissions per MJ of ethanol.

In terms of GHG emissions the additional emissions due to the complex logistics of BBS compared to OF are almost negligible, while the use of fertilisers in OF causes the worse performances of compared to BBS in terms of GHG emissions.

Although infrastructures were modelled in detail, these contribute for only about 3.3% to the total GHG emissions, with buildings and static machinery (ethanol plant and its components and sheds for the agricultural machinery) contributing for about 2% to the total GHG emissions, while moving machinery (tractors, harvesters, trucks and other agri-tools) contribute for the remaining 1.3%.

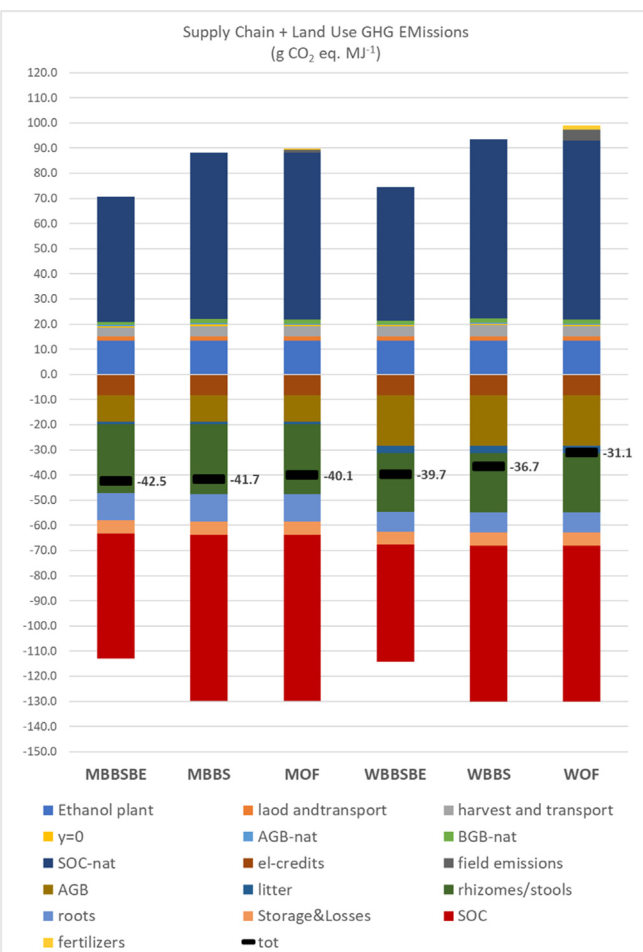

Fig. 6. GHG emissions of the six systems producing bioethanol (reference land use is already included in the results).

3.2.2. Eutrophication

For both marine and freshwater eutrophication, the biofuel systems show negative emissions thanks to the removal of nutrients with the harvest of the biomass (see Fig. 7). The emissions due to the supply chain are negligible compared to the amount of N and P removed by the plants. The results are similar for all the systems. The OF systems have lower N negative emissions because of the nitrogen leachate from fertilisers application, otherwise the eutrophying emissions of would be practically identical to the BBS because the N and P removed depends on the N and P content of the harvested biomass.

3.2.3. Airborne pollutants

All the biofuel systems show similar performances with regard to airborne pollutants (see Fig. 8). The only systems differing are the OF systems, where the ammonia emissions from fertilisers application cause a significant increase in airborne emissions (ammonia is both a precursor of secondary particulate formation and an acidifying substance). The ethanol plant provides the largest contribution to airborne pollutants emissions, and consequently to the disease incidence, mostly because of the auxiliary chemicals production and the internal combustion processes. Other sources are from diesel combustion in agricultural processes The slight difference between BBS and BE are ascribed to the lower emissions at y = 0, as in BBS the soil preparation and planting are spread over a larger amount of biofuel.

3.2.4. Resources depletion

All the biofuels show a limited need of fossil fuels for their production, between 0.11 and 0.15 MJ fossil energy per MJ ethanol produced (see Fig. 9), which means that the energy return over energy investment (EROEI) ranges from 6.7 to 9. The worse performances are found for OF systems because of the additional energy demand for fertilisers production. Most of the energy consumption takes place in the ethanol plant, followed by the diesel consumption for harvest and transport. The credits allocated to the coproduction of electricity are significant, higher than the total consumption from agricultural and transport diesel consumption, but lower than the consumption that takes place in the ethanol plant.

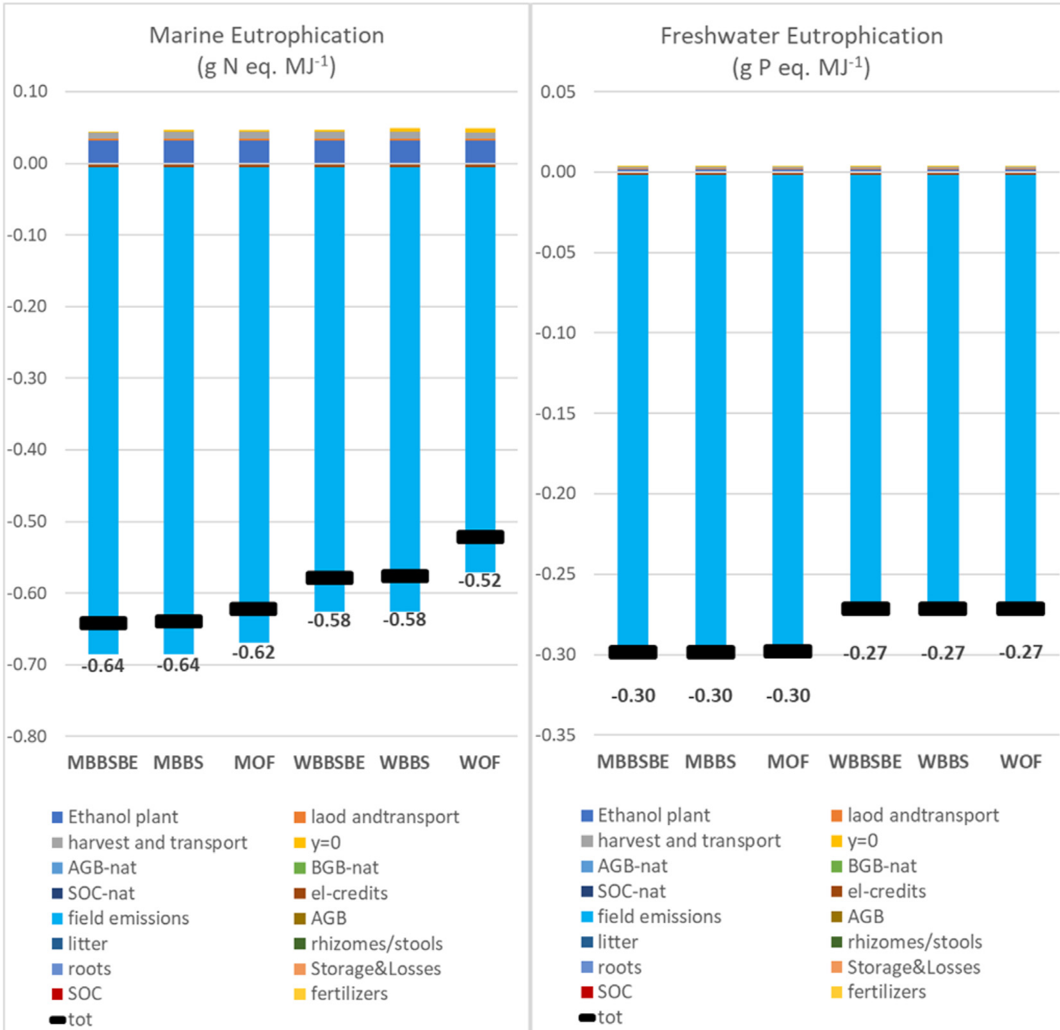

Fig. 7. Freshwater and marine eutrophication of the six systems producing bioethanol.

The depletion of minerals and elements follow the trends of the abiotic depletion of fossil energy. This metric is related to the consumption of resources for the manufacturing of the agricultural machinery, tractors, trucks, sheds and the ethanol plant and the auxiliary chemicals used for the ethanol production. In this case as well, the use of fertilisers in OF worsen the environmental performances.

Auxiliary chemicals contribute for about half the depletion of abiotic resources, while buildings, static machinery and agricultural and transport machinery contribute to about one fourth and one sixth of the total abiotic depletion elements. Fertilisers in OF provide a limited contribution of about one tenth to one twentieth for willow and miscanthus, respectively.

3.3. *Life cycle environmental impacts and comparison with alternative systems: third level*

3.3.1. *GHG emissions*

All modelled biofuels, when compared with potential alternatives for private mobility, outperform by a large extent the performances of the systems used for comparison (see Fig. 10). GHG emissions of cars running on bioethanol produced with miscanthus and willow are close to zero, ranging from −17 to 13.5 g CO_2 eq. vkm^{-1} while the alternative technologies range from 100.2 for the BEV REN, to 200.4 for the BEV, up to 343.2 g CO_2 eq. vkm^{-1} of the GAS. The negative emissions provided by land use, for the carbon storage related to the production of biofuel, practically balance out the emissions from the operation, maintenance and construction of the passenger car. Miscanthus performs better than willow, and buffer strips perform better than open field.

3.3.2. *Eutrophication*

The emissions of eutrophying substances is largely negative for bioethanol produced with miscanthus and willow thanks to their capacity of absorbing nutrients from the environment, for both marine eutrophication and freshwater eutrophication (see Fig. 11).

Regarding marine eutrophication, miscanthus performs better than willow, thanks to the higher content of N in the biomass. Moreover, OF pathways show worse performances than BBS pathways because of the nitrogen fertilisation in OF. Battery electric vehicles and ICE passenger cars have positive emissions, similar to those of BEV, showing larger emissions than GAS while BEV REN have lower emissions than ICE fossil passenger cars. The manufacturing of the cars and batteries and the production of the fuel/electricity are the most relevant contributors to this impact category for the pathways alternative to bioethanol.

Freshwater eutrophying substances emissions (phosphorus) are negative and equal for biofuel pathways based on the same crop, as

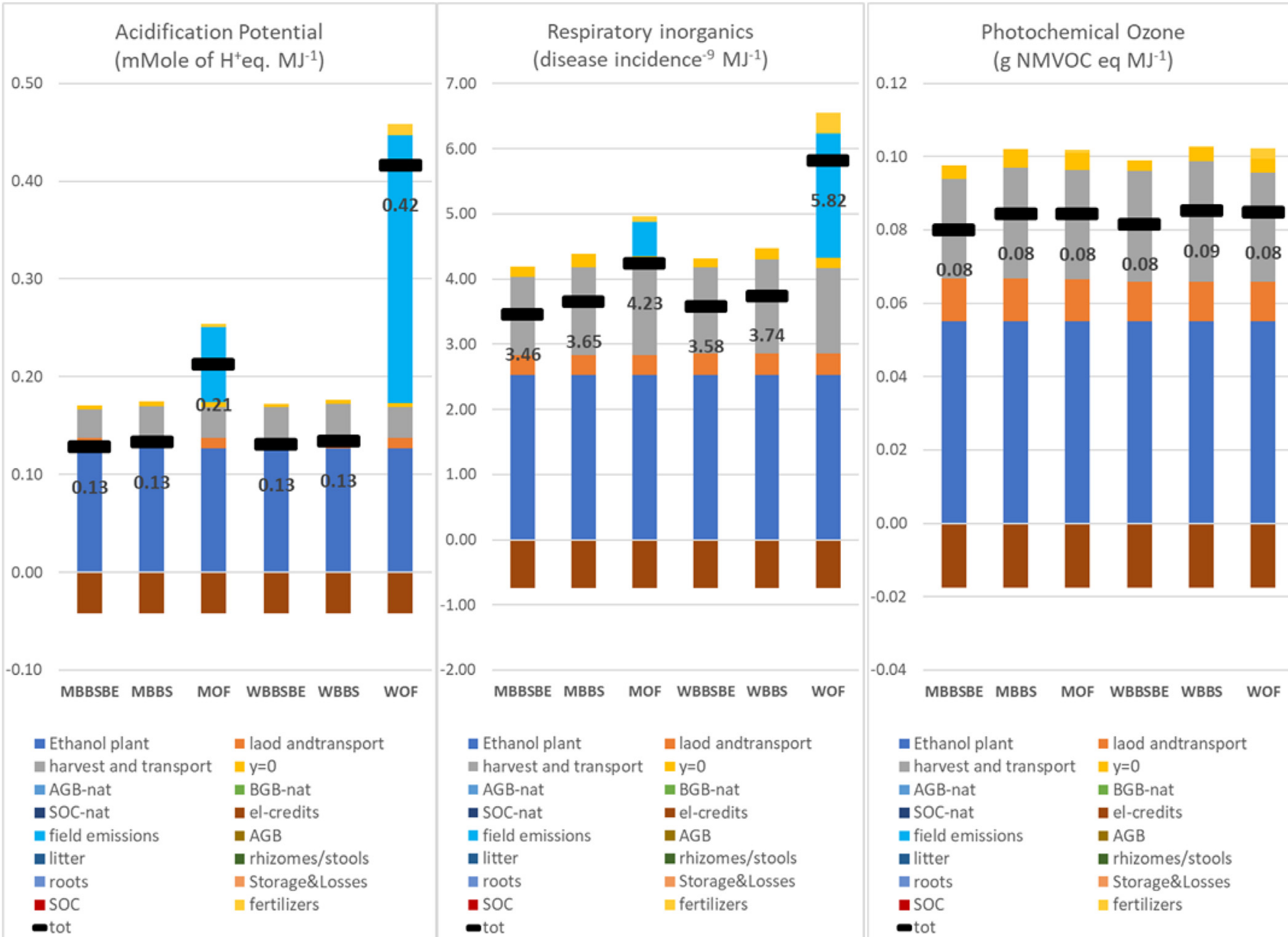

Fig. 8. airborne pollutants of the six systems producing bioethanol.

the P absorbed is proportional to the P content in the biomass and no crop is fertilized with P. For this impact category the emissions from the alternative, non-biofuel based pathways, are positive, with BEV emission similar to BEV REN, both twice the GAS, as the impacts of car and battery manufacturing, the major contributors to this impact category, are similar, but ICE cars do not require batteries.

3.3.3. Airborne pollutants

Photochemical ozone precursors emissions are similar for all the biofuel pathways, and unexpectedly, they are similar to GAS in both the total and the individual contributions (see Fig. 12). The major contributor is the passenger car manufacturing, followed by the fuel production, the fuel use and then the road construction and car maintenance. The BEV and BEV REN have higher emissions, though they do not have emissions from the fuel use, and the BEV REN has much lower emissions from electricity production, the emissions from maintenance are higher than any other contribution. We identified the source of these emissions in the use of ethylene glycol as cooling fluid, its replacement leads to significant ethene emissions.

Regarding acidification, again the emissions are similar for all the biofuel pathways but the OF, for which the use of fertilisers results in the highest emissions. Apart from the production of the fuel or electricity, in which again the use of fertilisers plays the most important role, the major contribution comes from the production of the passenger car and batteries.

Incidence of diseases related to respiratory inorganics is similar for all systems modelled. The production of passenger cars and batteries provides the largest contribution, followed by the fuel/electricity production. However, the particulate emissions during the operation of the passenger cars should receive a special attention, as it is more likely that they take place in densely populated areas. In the operation phase the disease incidence from BEV and BEV REN are about half of all the other vehicles, thanks to both the absence of exhaust emissions and lower emissions from brakes due to the regenerative breaking (see Fig. SM9).

3.3.4. Resources depletion

The consumption of elements and minerals is similar in all ICE cars, with most of the impact coming from the construction of the car and its maintenance. Battery electric vehicles require about 50% more resources for the construction of the battery, with BEV REN needing more materials than BEV for the production of photovoltaic panels (Fig. 13).

Running 1 km with a passenger car fuelled with bioethanol from miscanthus or willow requires about one third the fossil energy of a car running on fossil gasoline. Battery electric cars consume less fossil energy than bioethanol fuelled cars if running on renewables, while they need a higher amount of fossil energy if running on the current Italian electricity mix. For all the systems but the fossil and the BEV (for which the major contributor to fossil energy carrier

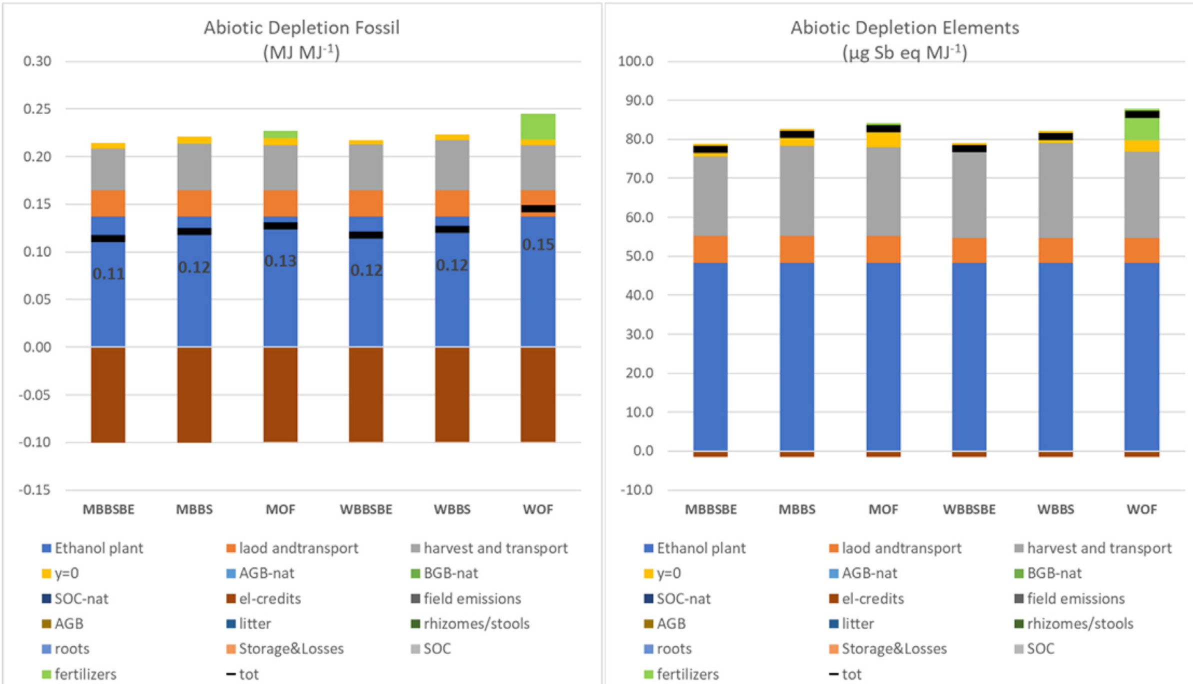

Fig. 9. abiotic depletion of the six systems producing bioethanol: fossil on the left, elements on the right.

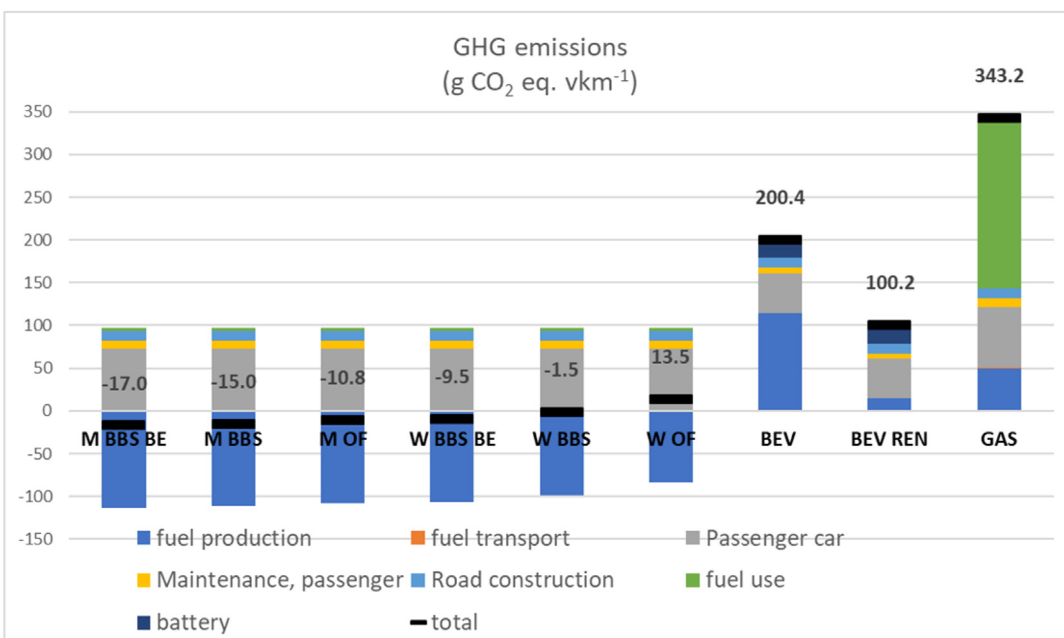

Fig. 10. Full life cycle GHG emissions for running 1 km with a medium sized passenger car.

consumption is fuel/electricity provision) the major contribution to fossil energy consumption is provided by the manufacturing of the passenger car and batteries.

3.4. Sensitivity analysis

As for all modelling exercises, many input data are rather uncertain, either because they are measured for other systems, or modelled with general formulae. However, given the limited contribution of the biofuel production to the final impacts per vkm (i.e. for the abiotic depletion categories), or the large magnitude of the difference between biofuels and other systems (i.e. eutrophication), our results are robust enough to draw significant conclusions.

However, for GHG emissions, the assumption that SOC accumulation is equal between BBS and OF has large impacts on the outcomes, resulting in a lower SOC accumulation per MJ in BBS BE, due to the higher production.

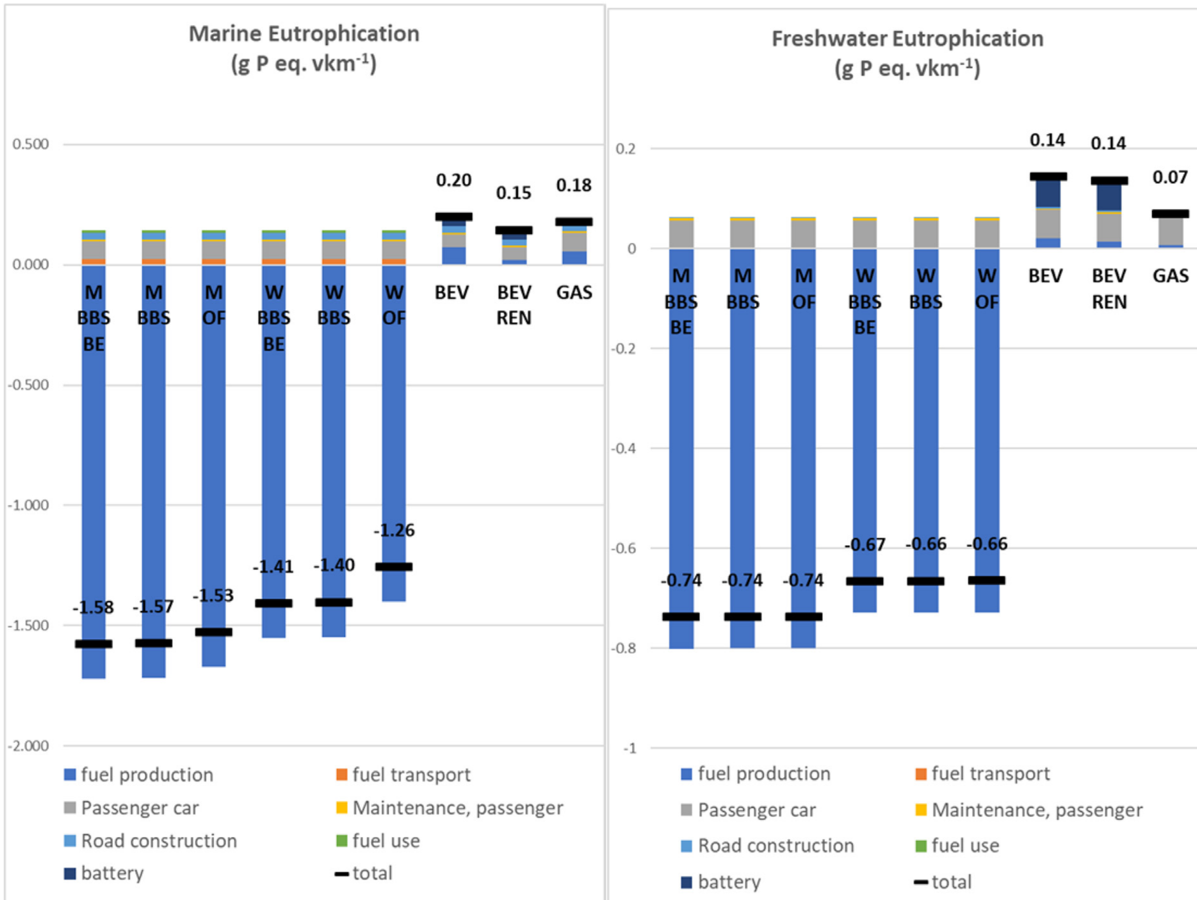

Fig. 11. Full life cycle emissions of eutrophying substances for running 1 km with a medium sized passenger car: marine eutrophication on the left, freshwater eutrophication on the right.

For miscanthus a positive crop-specific relationship between belowground C input based on crop yield and SOC changes over time has been demonstrated (Poeplau and Don, 2013). Large quantities of cumulated C input are retained in soil as SOC (Hansen et al., 2004). It is therefore likely that by producing additional biomass, the BBS BE systems would also accumulate more SOC. We have therefore increased the SOC accumulation in BBS BE by 32%, following the concept that additional biomass production would cause an additional input of organic matter to the soil from increased litter, harvest residues and roots. The same approach, based on the amount of biomass left on the field to calculate the SOC accumulation, is used in other studies, where an isohumic coefficient, representing the share of C in the residues reaching the soil that becomes stable SOC, is adopted (Badía et al., 2013; Sastre et al., 2015). The results change substantially, with GHG emissions from ICE passenger cars running on bioethanol from BBS BE becoming significantly negative and much lower than OF (see Fig. 14). GHG emissions per MJ of fuel resulting from this sensitivity analysis are reported in section 10 of the supplementary material.

4. Discussion

Our results clearly show that the cultivation of miscanthus and willow to produce second generation ethanol for private mobility is a good option for climate change mitigation. Bioethanol from miscanthus and willow cultivated both in BBS or OF have low supply chain GHG emissions. As recommended by Agostini et al. (2019), supply chain GHG emissions can only be used to evaluate potential hotspots in GHG emissions and identify measures to reduce supply chain emission with an eco-design approach. In this study, the additional logistic burden relative to the cultivation of miscanthus and willow on buffer strips do not generate a significant increase of GHG emissions related to the cultivation phase, as most of the emissions are proportional to the yield, rather than to the distance farm-field. The largest contribution to the supply chain emissions is related to processing and auxiliaries in the ethanol plant. As reported by Wiloso et al. (2012), this step is often overlooked at or oversimplified, probably because lignocellulosic ethanol is not yet available at commercial scale and many data are still proprietary.

In fact (Wiloso et al., 2012), found that many studies do not model in detail the ethanol plant, and especially enzymes production. For example (Lask et al., 2019), in a similar study on ethanol production from miscanthus, found that processing in the ethanol plant (including enzymes) is responsible for the emissions of 16–41 g CO2 eq MJ^{-1} while enzymes alone contribute with 12.2–15.1 g CO2 eq MJ^{-1}. In the same study, which used miscanthus as feedstock, the total supply chain emissions ranged between 29 and 61 g CO2 eq MJ^{-1}, with the large use of fertilisers heavily impacting the results.

Our results on the supply chain GHG emissions are in line with the results used by the European Commission in its recast of the Renewable Energy Directive (European Union, 2018) as detailed in Edwards et al. (2016) where GHG emissions from straw are

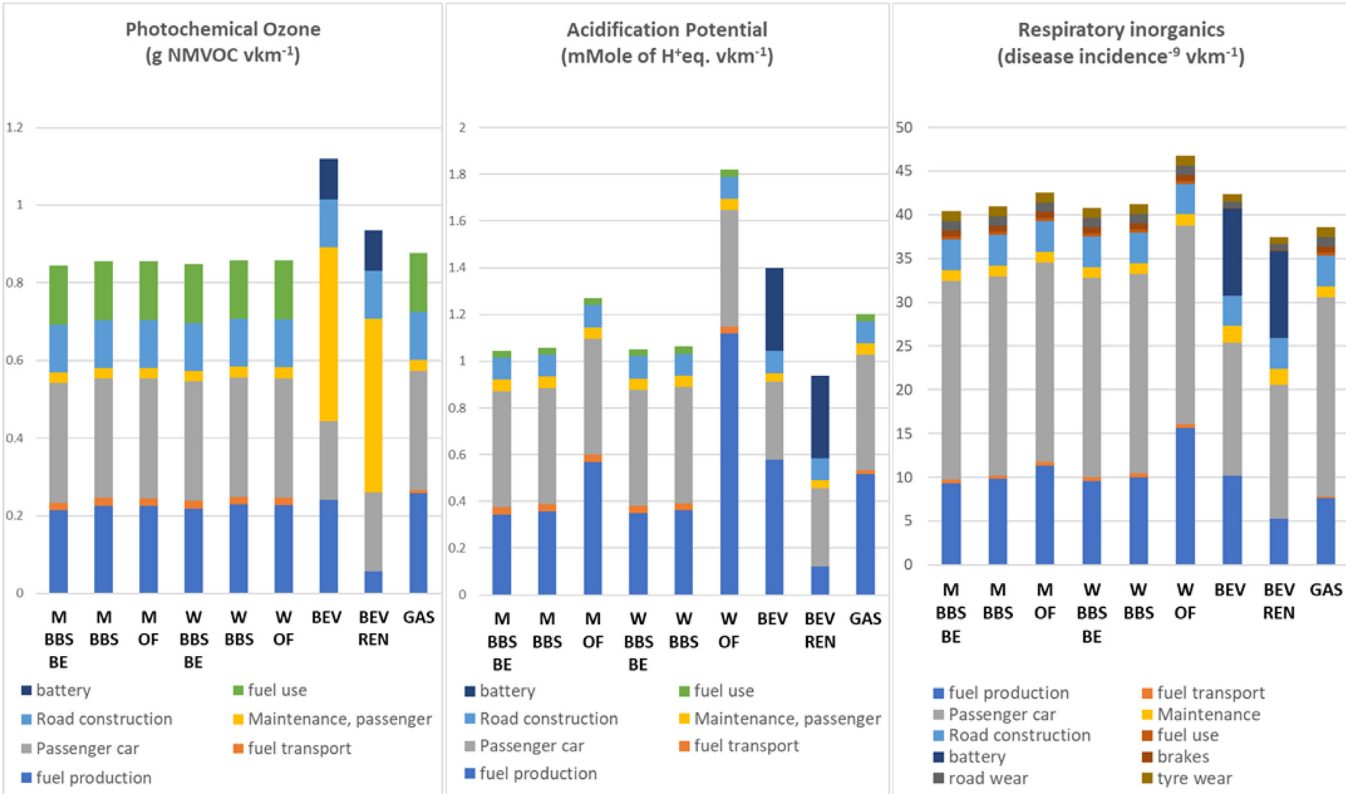

Fig. 12. Full life cycle emissions of airborne pollutants for running 1 km with a medium sized passenger car: photochemical ozone precursors on the left, acidifying substances at the centre, particulate matter on the right.

reported as 13.7 g CO2 eq MJ^{-1}.

When the analysis is expanded to include biogenic carbon, the GHG emissions from the supply chain are dwarfed by the biogenic carbon exchanges between the biosphere and the atmosphere. The total GHG emissions from the supply chain are about 30 g CO2 eq MJ^{-1} while the total exchange, including biogenic carbon amounts to about 180 g CO2 eq MJ^{-1}. In their methodological review both (Agostini et al., 2019; Wiloso et al., 2012) identified the exclusion of the biogenic carbon from LCA of bioenergy systems as an important issue, which may potentially mislead policymakers. In fact, in our case, when the biogenic carbon cycle is included in the analysis, the GHG emissions per MJ of fuel become negative thanks to the increased carbon sequestration in the biosphere compared to the reference land use. The influence of agricultural practices becomes practically nearly negligible, while the processing into ethanol provides only a limited contribution to the total GHG emissions. The accumulation of SOC, on the other hand, is the largest contributor to the net GHG balance. This is in agreement with IPCC (IPCC, 2019) which finds that strategies to increase SOC stocks have a significant role to play in climate change mitigation. However, it is important to notice that in this study we assumed that the cultivation of biomass feedstocks takes place in former arable fields and that in the absence of bioenergy cultivation, the naturally regenerated land would accumulate SOC as well, contrasting the effect of SOC accumulation in the perennial energy crop fields. Nevertheless, perennial crops store by far more carbon than natural grassland with native species, and we quantified this amount, which is what generates the negative emissions of the bioethanol pathways. This is the first time, to our knowledge, that this carbon pool is accounted in details for in LCA studies of lignocellulosic ethanol. Of course, other mitigation strategies could also be implemented on the same amount of land, especially for our OF scenarios, as afforestation strategies could generate similar or higher carbon benefits (Lewis et al., 2019).

Considering the full life cycle of the bioethanol produced, with its combustion in ICE passenger cars for private mobility, the negative emissions guaranteed by the biogenic carbon accumulation counterbalance the emissions from car manufacturing and maintenance, with the total emissions per km close to 0 (ranging from −17 to −3.5 g CO_2 eq vkm). When compared with other technologies providing the same function, it is evident that the other technologies considered are far from being carbon neutral and, for example, a BEV running on the Italian electricity mix has lower emissions than a gasoline vehicle, but if it runs twice the distance of the gasoline vehicle (e.g. because of the lower costs per km may increase the demand), it will then generate higher GHG emissions. Communicating this findings is fundamental to increase citizens, stakeholders, and policy makers awareness of the actual impacts on the climate of private mobility, where acting on the demand side is key to reduce GHG emissions.

The permanent and efficient root system of the perennial crops captures significant amount of nutrients, once in the biomass these are permanently removed from the environment, leading to negative nutrients emissions to fresh and marine waters. We could not find in literature LCA studies on lignocellulosic ethanol allocating negative emissions to the cultivation of bioenergy perennial crops because of their nutrients intake during growth. While the difference in eutrophication potential per MJ between OF and BBS is only partially evident, using a different metric, the kg of nutrients released per ha, as done by Battini et al. (2016), we find that the higher yield of BBS BE enables a higher removal of nutrients from the environment (see section 11of the supplementary material). On

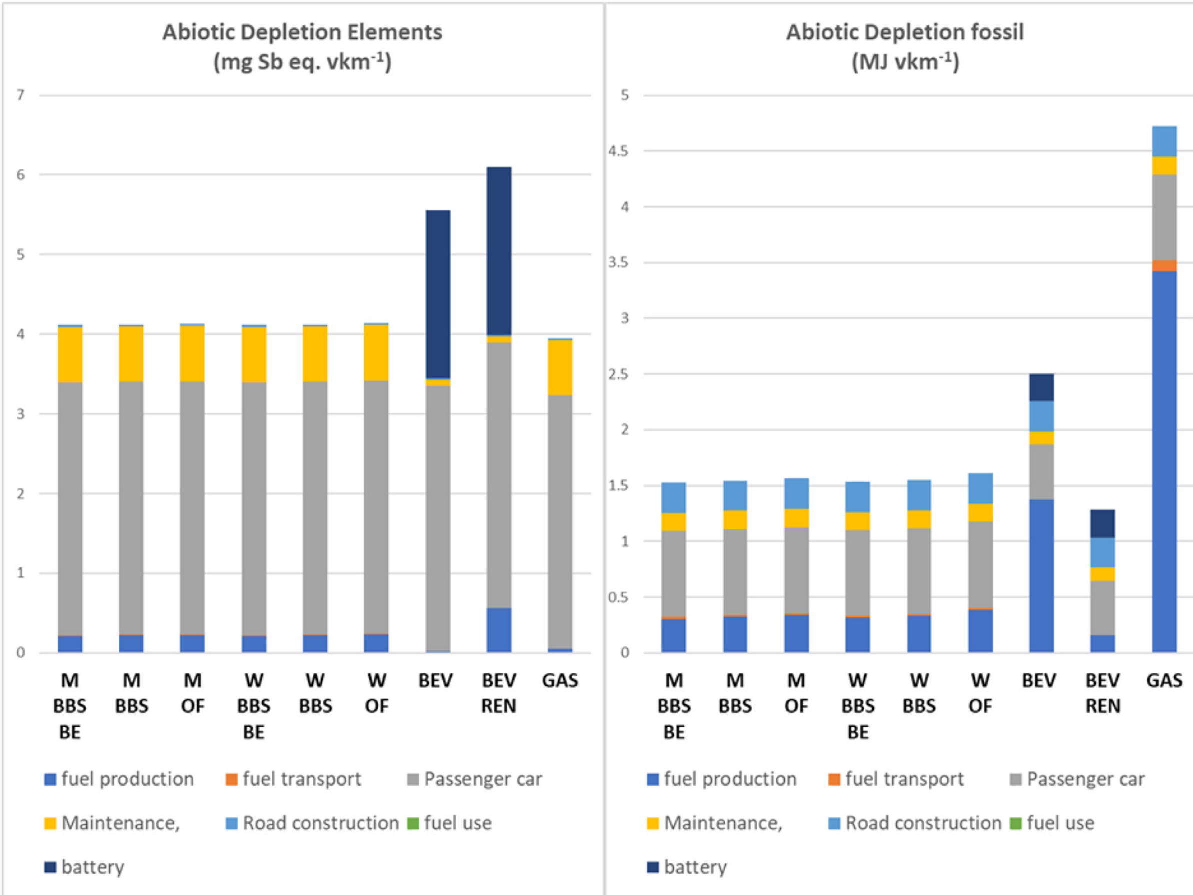

Fig. 13. Full life cycle abiotic depletion for running 1 km with a medium sized passenger car: abiotic depletion elements and minerals on the left, abiotic depletion of fossil energy on the right.

top of that, the removal of nutrients along the water streams in BBS, instead than in OF, is more significative, as the nutrients are diverted before they reach the ecological system where they have negative environmental impacts.

About airborne pollutant emissions, the biofuel pathways have similar performances, the only significative difference is due, as for eutrophication, to the use of fertilisers.

While the consumption of natural resources in the form of elements for bioethanol production is higher than fossil gasoline, the difference becomes negligible if we consider the full life cycle of the fuels, including their use in passenger cars. BEV, both running on renewables and the electricity mix, instead perform worse because of the use of abiotic resources for the battery manufacturing. About the consumption of natural resources in the form of fossil energy sources, the bioethanol fuelled vehicles outperform ICE passenger cars running on fossil gasoline by requiring one third of the fossil fuels and BEV by requiring 40% less fossil energy. Only the BEV REN, running on renewable electricity perform better than bioethanol fuelled cars. Considering only the supply chain, bioethanol pathways produce 6.6 to 9 times the amount of fossil fuel they require.

The inclusion of infrastructures in the analysis has shown that these are almost negligible in terms of GHG emissions and eutrophication if only the supply chain is considered, while these are responsible for the highest share of impacts for all the other impact categories. Thus, their inclusion in biofuel LCA is crucial for a comprehensive assessment.

All in all, we did not find any significant trade off among areas of environmental concern between the use of bioethanol from perennial energy crops cultivated in buffer strips and fossil gasoline in passenger cars, as the bio-fuelled vehicles perform better in all categories. While we found that these pathways could be considered GHG-free, since emissions of GHG were fully compensated by increased terrestrial C-sequestration.

To make the analysis fully comprehensive we have reviewed the available literature on the impacts of BBS on land ecosystem provision (see section 12 in SM). We found that BBS cultivation is an important factor for the enhancement of environmental services in intensive agricultural landscapes. Establishing a network of bioenergy buffers contributes to increase landscape connectivity and decrease disservices of agriculture such as soil degradation, biodiversity decline and water pollution.

The limitations of this study can be identified in the limited specificity of some input data. However, this is still the most consistent study in literature regarding input values, as most of the data were measured in the same field (SOC, AGB, BGB, yield) or modelled with a high level of detail (field operations, transport). Further, we recognize that we did not consider the dismission of the perennial crops plantation, and consequently also we did not test the permanence of the accumulated terrestrial C. However, in our case study, it is unlikely that in a close future annual crops will be cultivated again in place of BBS, while it is likely that perennial crops will be replanted or that the land will be left for natural regeneration. Thus, the SOC accumulated within the period assessed in our study would likely not be completely lost, and, additionally, the SOC accumulation might take place in a different field given that once the bioethanol plant is running, the demand

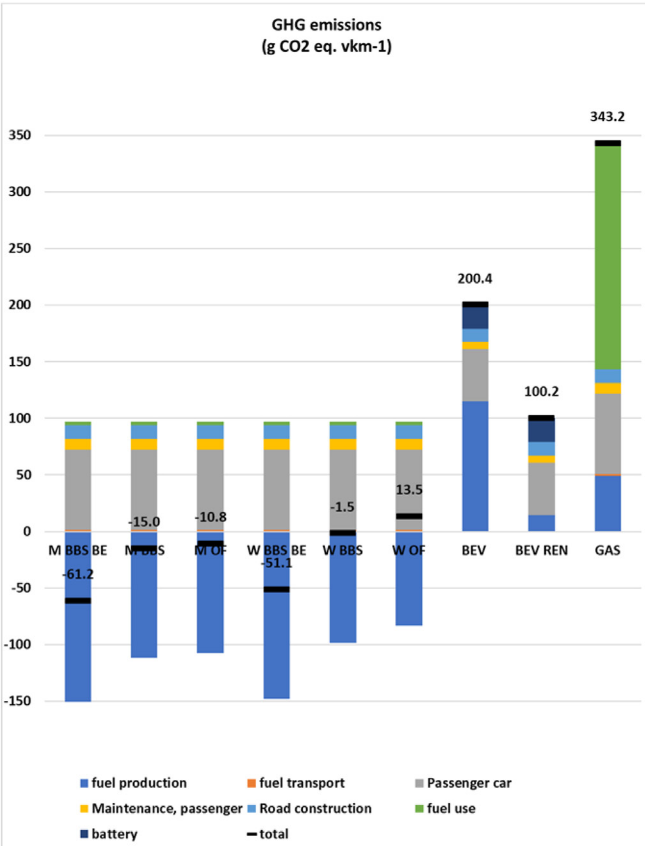

Fig. 14. Full life cycle emissions of GHG for running 1 km with a medium sized passenger car.

for perennial energy crops would remain. Therefore, we reckon our results would still be valid since there would be a mosaic of plantations with different ages, such as those that we modelled.

A key limitation of this study lays in the assumption that the cultivation takes place in former abandoned agricultural land. If the cultivation were to take place on active agricultural land, competing with other crops, for food, feed or fibres, the increased demand of land would generate pressure to take under human management additional natural ecosystems, with potential additional emissions from indirect land use change and negative impacts on two areas of environmental concern, which endanger the inhabitability of the planet o(namely land use and biodiversity (Steffen et al., 2015)). The results of this study are therefore meant to be specific of the systems modelled, and should not be interpreted as representative of bioethanol from perennials in general.

5. Conclusions

The results of this work show that a comprehensive approach to the assessment of the environmental performances of biofuel is fundamental to promote only pathways that do not generate significant trade-offs among areas of environmental concern. The inclusion of biogenic carbon exchanges, of nutrients cycles, of infrastructures, and the expansion of the life cycle to include the fuel use are essential to grasp the real impacts of biofuel production. By applying this holistic approach, we can conclude that our hypothesis is confirmed: the production of bioethanol from perennial energy crops grown in BBS is a win-win option for reducing the environmental impacts deriving from private mobility. In fact, the cultivation of perennial grasses (miscanthus) or short rotation coppice (willow) in BBS enables both the removal of nutrients from the environment and the removal of carbon from the atmosphere, reducing the anthropic burden on two critical environmental aspects which endanger the inhabitability of the planet. In addition, if the cultivation takes places in set aside agricultural land either because cultivation is not allowed (such as in buffer strips) or not convenient (abandoned or degraded land), the impact on biodiversity and land system change, the remaining environmental areas of concern in which the anthropogenic disruption are endangering the inhabitability of the planet, can also be positive. Although other land management choices might provide similar or higher benefits.

Regarding other areas of environmental concern, such as resources depletion or air pollution, the use of bioethanol from energy crops cultivated in bioenergy buffer strips does not show any significant trade off among the different environmental impacts as it results always lower than fossil gaasoline.

In our study, the cars fuelled with bioethanol perform better than electric vehicles in all the impacts categories analysed but acidifying substances and particulate matter emissions, where BEV REN perform slightly better. We find also that the use of fertilisers worsens all the environmental aspects of biofuel production.

The aim of this study is not to provide an exact emission value to be used in regulation, but rather to identify the hot spots and the relative contribution of all the processes involved in the biofuel production and use, from cradle to grave (field to vkm), to provide stakeholders and policy makers a broad and consistent understanding of the potential environmental impacts of bioethanol production and use from perennial energy crops in buffer strips.

The end users of this work's outcomes are policy makers at all administrative levels, from International and European Institutions to National, regional and local administrations who can recommend, or even mandate, the implementation of bioenergy buffer strips without concerns on their environmental sustainability. The outcomes of this research may also support the economic operators of the agricultural and biofuel sectors in investing in bioenergy buffer strips biofuels without risking a future change in the legislative framework. In addition, society as well will benefit from the implementation of bioenergy buffer strips thanks to an environmentally sustainable production of biofuels, which would guarantee the production of drop-in biofuels for those sectors that are difficult to decouple from fossil fuels' use and the contribution to rural development in terms of economic opportunities and job creation.

A key limitation of this study lays in the assumption that the cultivation takes place in buffer strips or former abandoned agricultural land, and therefore the results are to be considered applicable only in these contexts.

Future works will complement this study by including the dismission of these perennial cropping systems and the impact of reversion back to arable land on C and N cycling. The work may also be expanded to include the economic and social sustainability of biofuels from BBS.

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CRediT authorship contribution statement

A. Agostini: Conceptualization, Methodology, Visualization, Data curation, Writing – original draft, Writing – review & editing. **P. Serra:** Data curation, Investigation. **J. Giuntoli:**

Conceptualization, Methodology, Writing – review & editing. **E. Martani:** Data curation, Investigation. **A. Ferrarini:** Data curation, Investigation, Visualization. **S. Amaducci:** Conceptualization, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.126703.

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