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Environmental performance of gasified willow from different lands including land-use changes

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Abstract

A life-cycle assessment (LCA) of a low-input, short rotation coppice (SRC) willow grown on different Danish lands was performed. Woodchips are gasified, producer gas is used for cogeneration of heat and power (CHP), and the ash-char output is applied as soil amendment in the field. A hybrid model was developed for the estimation of greenhouse gas (GHG) emissions from indirect land-use changes (iLUC) induced by willow cropping on arable land (iLUC_{food}). For this, area expansion results from a general equilibrium economic model were combined with global LUC trends to differentiate between land transformation (as additional agricultural expansion, in areas with historical deforestation) and occupation (as delayed relaxation, DR, in areas with historical land abandonment) impacts. A biophysical approach was followed to determine the iLUC_{feed} emissions factor from marginal grassland. Land transformation impacts were derived from latest world deforestation statistics, while a commercial feed mix of equivalent nutritive value was assumed to substitute the displaced grass as fodder. Intensification effects were included in both iLUC factors as additional N-fertilizer consumption. Finally, DR impacts were considered for abandoned farmland, as a relative C stock loss compared to natural regeneration. ILUC results show that area related GHG emissions are dominant (93% of iLUC_{food} and 80% of iLUC_{feed}), transformation being more important (82% of iLUC_{food}) than occupation (11%) impacts. LCA results show that CHP from willow emits 4047 kg CO₂-eq ha⁻¹_{occup} (or 0.8 gCO₂-eq MJ⁻¹) when grown on arable land, while sequestering 43 745 kg CO₂-eq ha⁻¹_{occup} (or -10.4 gCO₂-eq MJ⁻¹) when planted on marginal pastureland, and 134 296 kg CO₂-eq ha⁻¹_{occup} (or -31.8 gCO₂-eq MJ⁻¹) when marginal abandoned land is cultivated. Increasing the bioenergy potential without undesirable iLUC effects, especially relevant regarding biodiversity impacts, requires that part of the marginally used extensive grasslands are released from their current use or energy cropping on abandoned farmland incentivized.

Keywords: biochar, bioenergy, gasification, iLUC, LCA, marginal land, SRC willow

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Introduction

In the light of the Peak Oil and Global Climate Change, a gradual shift in the energy provision from fossil to renewable sources has ensued in many industrialized countries since the Kyoto Protocol (UNFCCC, 1998). Despite the ongoing debate around the net benefits and impacts, it is unquestionable that biomass will play a key role in the future not only as provider of different chemicals and materials in biorefinery parks but also as energy carrier (WBGU 2008; Bauen *et al.*, 2009; IPCC 2012; Ruppert *et al.*, 2013; Slade *et al.*, 2014). From a technical point of view, biomass is a good candidate to complement other fluctuating renewable energy

sources, compensating for an intermittent supply in a transitioning power grid that may lack the necessary demand flexibility and energy storing or transmission capacity. It is expected that biomass will make up to 56% of the renewable energy supply (or 12% of the total primary energy supply) in the European Union (EU) by 2020 (Beurskens *et al.*, 2011).

The sustainability of first generation biofuels was put into question 8 years ago by the first study to include indirect land-use change (iLUC) emissions (Searchinger *et al.*, 2008). After these, many followed showing that when all life-cycle and indirect impacts are included, certain bioenergy crops may emit an amount of greenhouse gas (GHG) comparable to or larger than the fossil fuels they intend to replace (Fargione *et al.*, 2008; Reijnders & Huijbregts, 2008; Fritsche *et al.*, 2010). Dedicated energy crops may also compete with food for limited land and freshwater resources (Foley *et al.*, 2005;

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Gerbens-Leenes *et al.*, 2009), which can make poor people even more vulnerable and drive socio-political conflicts (Homer-Dixon, 1994, 1995; WBGU, 2008). The crops that are displaced by bioenergy crops thus increase pressure on biodiversity wherever they are brought into production (Koh, 2007; Butchart *et al.*, 2010; Dale *et al.*, 2010). To avoid these problems, biological residues and biomass grown in marginal farmlands have been pointed as a solution to the food-energy-environment *trilemma* (EEA, 2005; Tilman *et al.*, 2009). A European review of biomass resource assessments for energy concluded that residues from agriculture and forestry are not likely to increase significantly in the future (Bentsen & Felby, 2012). Dedicated energy crops grown on marginal lands are thus expected to meet the major part of the increasing biomass demand in EU (4.5 EJ yr⁻¹) by 2020 (Bentsen & Felby, 2012). Studies that claimed environmentally sound bioenergy from marginal lands did not consider though the iLUC related to the current use of these lands (Tilman *et al.*, 2006; Gelfand *et al.*, 2013). Similarly, many other life-cycle assessments (LCA) of short rotation coppice (SRC) willow for energy have left out these potential impacts (Heller *et al.*, 2003; Keoleian & Volk, 2005; Börjesson & Tufvesson, 2011). On the other hand, if the target marginal land is abandoned then a spontaneous, site-dependent, natural regeneration process ought to be considered (Milà i Canals *et al.*, 2007a,b; Koellner *et al.*, 2013).

Short rotation coppice plantations are low-input high-yielding cultivation systems of fast-growing woody species such as poplar (*Populus* spp.) and willow (*Salix* spp.). They were already studied to investigate their potential in marginal lands 30 years ago (McElroy & Dawson, 1986) and have more recently been investigated for their large-scale potential in different North European and American soils and climates (Stolarski *et al.*, 2011; Sevel *et al.*, 2012; Amichev *et al.*, 2014). Due to the difficult economic viability of current SRC agri-systems, and after the suspension of EU's set-aside programme that supported nonfood crops, most of the bioenergy production takes place on fertile cropland (Don *et al.*, 2012), which puts their sustainability into question (Beringer *et al.*, 2011; Dauber *et al.*, 2012).

The objective of this study was to elucidate the conditions, with focus on the land types, under which willow cropping in Denmark can be environmentally beneficial for the next 20 years, when produced biomass is used for decentralized cogeneration of heat and power (CHP) through gasification. For this, an exploration of different reference land scenarios has been carried out, including iLUC effects and the offsetting of carbon and nutrients from applying biochar-ash residues as soil amendment. The LCA has been complemented by a qualitative assessment of potential biodiversity impacts.

Materials and methods

Life-cycle assessment

Goal and scope. An LCA has been carried (ISO 2006a,b), following a mix of consequential (which investigates the most likely consequences of a given change within the economic system and the studied subsystems (Ekvall & Weidema, 2004)) and scenario-based approaches (which look at a broader range of possible outcomes). As the focus has been put on the effects of occupying different land types in Denmark, the functional unit of our dedicated bioenergy system is the 'management of one Danish hectare land (1 ha) for energy purposes'. This is also in line with LCA expert recommendations, as land is the main natural resource (and bottleneck) for energy cropping (Cherubini *et al.*, 2009; Pawelzik *et al.*, 2013). Notwithstanding, and given that any biofuel needs to replace a fossil fuel counterpart, the results are also provided on a per megajoule basis for comparison. Therefore, three basic scenarios have been deployed according to their reference land use (see subsection Reference land-uses). The time scope for the assessment is the duration of a full rotation of SRC willow, 20 years.

System boundaries and impact method. A set of four impact categories at the midpoint level, which are the most relevant for dedicated biofuels (Bringezu *et al.*, 2009), was selected from the CML 2001 (November 2009 version) impact assessment method: the global warming potential (GWP, cumulative radiative forcing of GHG emissions over 100 years), the eutrophication potential, the acidification potential and the toxicity potential (calculated as an aggregate of all toxicity impacts). Land use is not considered as separate midpoint indicator, but land-use changes (LUC) calculated as a previous step to derive GW impacts. These are classified as indirect and direct LUC (iLUC and dLUC, respectively, see section 'Direct and indirect LI+UC emissions') and further subdivided into transformation and occupation impacts (TI and OI, respectively). TI refers to land conversion impacts which arise from the transformation of ecosystems to facilitate agriculture (e.g. GHG emissions from deforestation) and are assumed to happen instantaneously. OI refers to land-use impacts arising from continuing the utilization of land for agricultural purposes (e.g. GHG emissions from farming activities like fertilization) and extend over the time of land occupation. The system was modelled in the LCA software GABI 4.4 using primary data for the cultivation activities in the foreground system and data from the database Ecoinvent 2.01 for other processes. All agricultural processes and machinery used for the preparation of the willow plantation were included, as well as those for transporting and gasifying the resulting woodchips and spreading the ash-char residues. Soil was considered down to 1 m depth, which applies to the soil organic carbon (SOC) changes considered.

The energy conversion system was modelled as a 500 kW_e output decentralized gasification plant for CHP. Ideally, a system analysis model representing the energy markets involved should be used for the identification of the future marginal energy supplier (Münster & Meibom, 2010), which would potentially be replaced by the energy from the gasification

process. At the current development stage, the modelled gasification reactor would replace coal-based CHP. This is due to high initial investments of small CHP plants and the slow start-up of the reactor when cold, which makes it suitable for base-load CHP (Energinet 2012). However, the gasification reactor may be enhanced in the future with additional flexibility features, as it is a novel technology under ongoing development (an 'energy storage' or flexibility feature is being investigated through conversion of the producer gas into methane for its introduction into the natural gas grid, J. Ahrenfeldt, personal communication). In that case, our willow gasification system would substitute natural gas-based CHP. In this study, natural gas was assumed as the displaced marginal energy and coal was left for the sensitivity and uncertainty analysis.

Following experimental results from literature, gasification ash residues were assumed to substitute a fraction of the conventional synthetic P-K fertilizers: superphosphate (P_2O_5) and potassium oxide (K_2O) – no nitrogen remains in the ash (Kuligowski *et al.*, 2010; Müller-Stöver *et al.*, 2012). Finally, temporary biogenic carbon storage in the soil was not considered as it has been proved to be irrelevant for fast-growing SRC plantations (Cherubini *et al.*, 2011). Permanent carbon storage from the application of the carbon rich fraction of the ash (biochar) to the soil was assumed, given that its long-term stability is confirmed by different studies and sources (Kawamoto *et al.*, 2005; Glaser, 2007).

Even though 'idle' land provides ecosystem services that are valuable (and sometimes crucial) for humans (Zhang *et al.*, 2010a,b; UNEP, 2005), the quantification of other impacts (e.g. on soil quality) was left out of the scope of this study. Nevertheless, a qualitative assessment of biodiversity impacts of different land uses (key for dedicated biofuels) has been included in the discussion.

Reference land uses. From a consequential point of view, the most likely alternative use of the lands considered for the energy

cropping should be used as reference or baseline for the determination of the land-use impacts (Milà i Canals *et al.*, 2007b). However, the uncertainty of future uses of Danish marginal land is high, as it will heavily depend on large-scale political decisions: Europe's Common Agricultural Policy (CAP) framework's support schemes (EEA, 2009); national and European renewable energy targets (European Union, 2009; The Danish Government, 2011); global treaties for climate change mitigation (United Nations, 2015); and trade liberalization agreements (e.g. TTIP) (Laborde, 2011). To compensate for this uncertainty, different scenarios have been developed. Overall, we consider three land-use scenarios for the reference situation: (i) arable land; (ii) extensively used marginal land; (iii) abandoned marginal land. These represent most of the likely land resources for dedicated bioenergy cropping in EU and Denmark.

For the arable land scenario, *business-as-usual (BAU) land management for wheat production* was adopted as reference (REF1). Being impossible to know how the displaced crops are produced (i.e. what kind of inputs in which amounts are used where), we assumed that the same total inputs as in Denmark are applied to achieve the same total output of wheat. For marginal lands, given their inherent uncertainty, two reference land-use scenarios were deployed: *extensively managed permanent grassland* (REF2) and *abandoned farmland with natural regeneration* (REF3). The continued OI for the abandoned farmland scenario (REF3) is also known as 'delayed relaxation' impacts (denoted as DR, hereafter), because they postpone the natural relaxation that would take place without the studied activity. A graphical illustration of these reference land uses can be seen in Fig. 1.

Inside the arable land scenario, an emission factor was included to account for iLUC effects ($iLUC_{food}$, see iLUC hybrid model for the arable land: $iLUC_{food}$). For consistency, three references were implemented which apply to three different types of land affected (see Table 1). For the first, a *natural vegetation cover in steady state* (REF4) was assumed for the areas where historical land expansion was identified (transformation

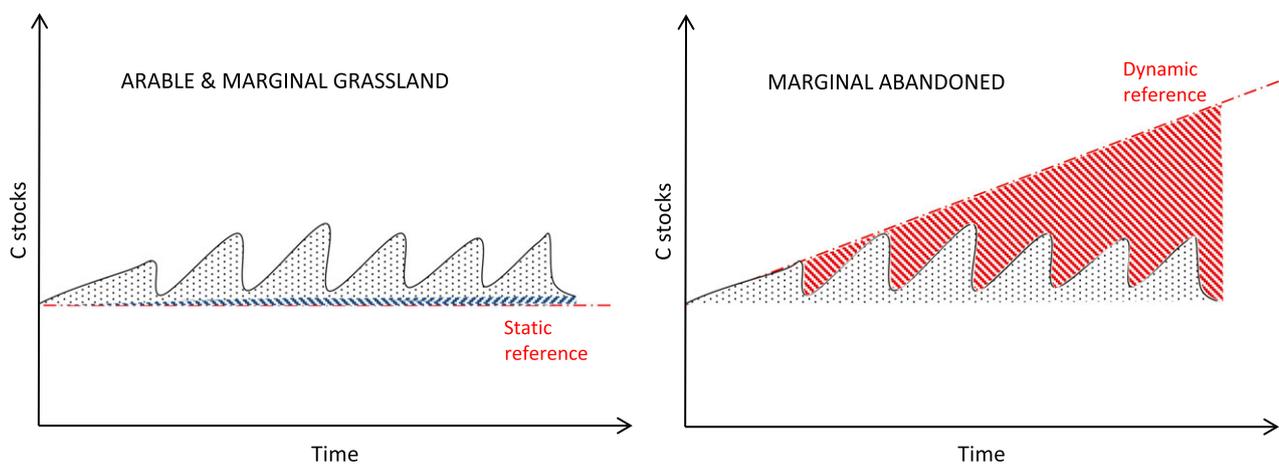


Fig. 1 Illustrative figure of the evolution in C stocks in SRC willow cultivation on different types of land. The saw-teeth (shaded in black dots) represent the 3-year harvesting rotations. Left: the small blue striped area under the saw-teeth represents the small SOC gain achieved by SRC willow. Right: the red striped area below the dynamic reference implies a C stock deficit of SRC willow with respect to natural regeneration.

Table 1 Framework for a consistent application of reference land uses along the assessment.

Arable land		Marginal grassland		Marginal abandoned
dLUC	iLUC _{food}	dLUC	iLUC _{feed}	dLUC
REF1 (static): BAU wheat production (OI)	REF3 (dynamic): Natural regeneration (DR) REF4 (static): Natural vegetation cover (TI) REF5 (static): Local arable management (OI)	REF2 (static): Extensive pasture management (OI)	REF4 (static): Natural vegetation cover in steady state (TI) REF5 (static): Local arable management (OI)	REF3 (dynamic): Natural regeneration (DR)

impacts, TI). For the second, a natural regeneration reference (REF3 again) was taken for the delayed relaxation (DR) impacts (Müller-Wenk & Brandão, 2010), in the areas where historical land abandonment was identified. For the third, *local agricultural management* (REF5) was assumed for the areas where intensification took place. The specific areas where intensification occurred were unknown, thus linearity between impacts and increased N-application was assumed.

Another iLUC emission factor was added to the GHG budget of the marginal grassland scenario (REF2), to account for the effect of displacing the grass that would otherwise be grazed by cattle (iLUC_{feed}). The iLUC_{feed} factor was developed with a biophysical approach (see section iLUC model for the marginal extensive grassland: iLUC_{feed}). This implied that, differently from the iLUC_{food}, DR impacts could not be predicted (only REF4 and REF5 references were considered) (see Table 1).

The life-cycle inventory. Field data were taken from a perennial SRC willow plantation established in 2010 in an area next to Roskilde, Denmark. The field is harvested every third winter, with a total of six rotations in a 20 year full cycle. Primary data (as total consumption of diesel per operation) were used for most of the farming operations, complemented with Ecoinvent 2.01 data and other literature to fill gaps. The plantation is fertilized every third year after harvest with NPK (21 : 3 : 10), at individual rates of 120 kg N ha⁻¹, 15 kg P ha⁻¹ and 56 kg K ha⁻¹. Targeted chemical weed control was minimized and applied only before planting and after coppicing. Other field emissions (N₂O, NO₃⁻, NH₃, NO_x, NMVOC, P) were calculated following the IPCC guidelines (Smith *et al.*, 2003; IPCC 2006) and using the figures in the extensive life cycle inventory (LCI) for Danish conditions developed by Hamelin *et al.* (2012). Woodchips are transported after the combined harvesting–chipping process in a cargo lorry to the cogeneration plant. Yield and plant residues were extrapolated using our harvest data of 2013, and the residue fractions from Lindroth & Båth (1999) and the growth data from the long-term experiments carried out by Lærke (2010) and Sevel *et al.* (2012). All inputs were assumed to be the same for the three scenarios, differing only in the soil type and the incurred iLUC. The soil type affects the outputs of each scenario, in terms of different nutrient leaching, SOC changes and yields achieved (Hamelin *et al.*, 2012; Sevel *et al.*, 2012) (see section ‘Direct and indirect LUC emissions’).

The gasification unit is a highly efficient two-stage, downdraft unit that is fed with willow chips from the field and is coupled to

a set of gas engines for small-scale CHP (Henriksen *et al.*, 2005; Ahrenfeldt *et al.*, 2013). Emission data for the gasifier were taken from Ahrenfeldt (2007), while the thermal and electrical efficiencies were taken from Ahrenfeldt *et al.* (2013), where expected performances of the upscaled plant (500 kW_e) are shown.

The bioash–biochar soil amendment is mixed and applied with the rest of the fertilizer, after first harvest. Specific data about the bioash and biochar residue output and content were taken from Hansen *et al.* (2014). In our study, the bioashes have been accounted for their fertilizing potential and implemented as avoided synthetic fertilizer production, extrapolating their plant availability from literature data (Kuligowski *et al.*, 2010; Müller-Stöver *et al.*, 2012). The biochar or black carbon fraction of the ash residues has been considered as permanent carbon sequestration in the assessment, as it is expected to remain in the field for centuries (Nishimiya *et al.*, 1998; Kawamoto *et al.*, 2005; Lehmann *et al.*, 2006; Glaser & Birk, 2012). For more details, see Appendix S1.

Direct and indirect LUC emissions

Direct LUC emissions. Direct LUC emissions are those arising directly as a consequence of a change in the management and use of the concerned land. These have traditionally been the only land-use impacts considered in LCA studies, e.g. Reijnders & Huijbregts (2008) and Börjesson & Tufvesson (2011). The focus of this section is on CO₂ emissions caused by changes in above-ground and below-ground biomass pools of carbon (BioC) and SOC changes. For simplicity, the C stocks under the management systems of REF1 and REF2 have been assumed to remain constant (‘static references’) (left side illustration in Fig. 1). The reference land use for the marginal abandoned land is natural relaxation (‘dynamic reference’, REF3) with a steadily increasing C stock (right side illustration in Fig. 1).

For the arable land scenario, BioC changes were neglected as above-ground biomass is harvested as woodchips, stumps are removed at the end of the rotation cycle, and fine roots and litter are eventually respired or converted to SOC. An estimated SOC change rate of 28.5 kg C ha⁻¹ yr⁻¹ was adopted from Hamelin *et al.* (2012) (Table S18, Appendix S6). Such a small SOC gain from the arable to SRC cropping can be explained by the common, long-time applied manure fertilization in Danish croplands. This unusually high organic fertilization has kept SOC content of Danish fields remarkably high. The adopted SOC figure is expected to be representative for this case, as the

soil characterization from October 2014 (see Appendix S2) was in line with their soil classification and initial SOC content assumption. Our field, a sandy clay loam, showed an average SOC content of $148.6 \pm 74.9 \text{ Mg C ha}^{-1}$, while in Hamelin *et al.* (2012), the initial SOC was $144.7 \pm 76.4 \text{ Mg C ha}^{-1}$ for a sandy loam, under the 'willow, 100% mineral fertilizer, dry climate' scenario. In their study, the SOC change was calculated using the C-TOOL model, which is an agricultural soil carbon flow model calibrated for Danish conditions and validated with historical agricultural data (Petersen *et al.*, 2002, 2013).

For the marginal extensive grassland scenario, a SOC gain of $153.4 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ was applied, as an average soil C change of grassland transitions to SRC (from two meta-analyses on LUC: Guo & Gifford, 2002 and Harris *et al.*, 2015). Both studies reached similar conclusions: 2% and 3.7% mean annual SOC gains, respectively. For the same reasons as in the arable scenario, BioC changes were also neglected.

For the marginal abandoned land scenario, a relative SOC loss of $31.5 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ was calculated as the difference between the SOC change from willow cultivation on cropland (from Hamelin *et al.*, 2012) and the SOC change under natural regeneration. The SOC change for this dynamic reference was considered as a constant gain until reaching a final SOC level of 167 Mg C ha^{-1} (representative of a Danish JB5 forest soil, as reported in Krogh *et al.*, 2003) after 500 years. The BioC change was calculated with the above-ground (trunks, branches and litter) and below-ground (roots) biomass C that would have been accumulated by the vegetation during the time scope of the assessment. Again, this process was linearized to implement a constant annual carbon stock change, taking the total BioC of a managed beech forest as the 100-year endpoint (Wu *et al.*, 2013). Computed this way, the willow SRC has a BioC deficit (compared to the dynamic reference) of $4116 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ yr}^{-1}$. More information can be found in Appendix S3.

iLUC model for the marginal extensive grassland: iLUC_{feed}. Even if Danish permanent pastures may be classified as marginal from an economic point of view, they are still used in an extensive way – hence their name. It was thus assumed that the displaced grass is fully substituted with a commercial feed mix of soya bean meal and maize grain of an equivalent nutritive value. A biophysical approach was followed here for the calculation of iLUC emissions derived from these grasslands, after Tonini *et al.* (2015). The iLUC_{feed} emission factor is the sum of two components: the land transformation (iLUC_{feed_TI}) and the intensification (iLUC_{feed_intensif}) factors. Taking deforestation statistics and world average shares of expansion–intensification for food production (from FAO), the annual global demand of new land could be estimated. With this, the iLUC_{feed_TI} factor was calculated as an average of global deforestation trend per demanded area. The impacts from deforestation were calculated with IPCC data for global biome C stocks and GHG emission factors (IPCC, 2006b,c). The iLUC_{feed_intensif} factor was calculated as the production and use of the additional N-fertilizer, assuming the world average change in use of N-fertilizer for intensification, derived from FAO's global time series. Finally, iLUC_{feed} was corrected with a commercial feedstock area-equivalent factor, based on the nutritive value of the grass displaced. For more information see Appendix S4.

iLUC hybrid model for the arable land: iLUC_{food}. The present iLUC_{food} model was built according to the UNEP-SETAC guideline for global land-use impact assessment on biodiversity and ecosystem services in LCA (Koellner *et al.*, 2013). The land-use cover typology and the bio-geographical differentiation were slightly modified and adapted from the inventory of Kløverpris *et al.* (2008) to fit in the classification of the LCI principles for global land use (Koellner *et al.*, 2012) and the recommended ecoregion classification (Olson *et al.*, 2001). The suggestions for the reference land use (always natural relaxation) and the modelling period (500 years) were not followed. This is because this study aims at integrating, rather than focusing exclusively on, land-use impacts in LCAs of dedicated bioenergy systems. Therefore, a 100-year modelling period was chosen and multiple references used as a compromise solution (see Table 1).

An economic area expansion model and a biophysical land-use intensification model were combined to estimate the total iLUC_{food} emission factor. The reason for this hybrid approach was to cover all downstream GHG emissions that the occupation of arable land for energy cropping triggers. These include TI (as new agricultural area expansion onto native ecosystems), DR (in marginal lands that were in the process of being abandoned) and intensification impacts (as increased application of synthetic fertilizers in existing cropland). TI and DR impacts were calculated using the area expansion output (A_{iLUC}) of a general equilibrium economic model (Kløverpris, 2008), discerning among land expansion or land abandonment areas from historical LUC trends (Ramankutty & Foley, 1999; Ramankutty *et al.*, 2008; Kløverpris, 2009). Even if the model from Kløverpris (2008) included short-term effects (e.g. price changes), food demand was assumed to remain constant, and therefore, a full supply of wheat was considered in the long run. Regionalized characterization factors (CF) per area expanded (in $\text{Mg C ha}_{\text{exp}}^{-1}$) were produced for identified land transformation and occupation processes (specified in Table 3 under Results). These were multiplied by the area expansion per region per tonne wheat demanded (A_{iLUC}) and the average Danish wheat yield, which gave all TI and DR impacts per area demanded (in $\text{Mg CO}_2\text{-eq ha}_{\text{dem}}^{-1}$). A duration factor, as suggested by Müller-Wenk & Brandão (2010); was applied to the relevant DR impacts. These were aggregated into a single, annualized iLUC_{food_area} score (see Table 3). The biophysical model to calculate the emissions from intensification was the same as in the iLUC model for the marginal extensive grassland (iLUC_{feed_intensif}). The intensification share used in the economic model (instead of global averages as in iLUC_{feed}) was finally applied to iLUC_{food_intensif} to come up with the total iLUC_{food} factor (see Table 2 under section 'Results'). For a detailed explanation, see Appendix S5.

Results

iLUC model results

iLUC_{food}. The hybrid approach allowed differentiating between three basic iLUC effects: transformation, DR and intensification impacts, which are triggered as a

Table 2 Annualized iLUC factors for arable and marginal grassland (per ha_{occup})

iLUC factors	Reference land use	Area ratio (A_{iLUC}/A_{SRC})	Annualized GHG emissions (kg CO ₂ -eq ha ⁻¹ _{occup} yr ⁻¹)	Share (%)
iLUC_{food}				
iLUC _{food_TI}	REF4	0.881	11714.7	82
iLUC _{food_DR}	REF3	0.319	1559.5	11
iLUC _{food_intensif}	REF5	0.515*	962.2	7
Total iLUC _{food}		1.715*	14236.4	100
iLUC_{feed}				
iLUC _{feed_TI}	REF4	0.345	7436.3	80
iLUC _{feed_intensif}	REF5	0.588*	1885.3	20
Total iLUC _{feed}		0.933*	9321.5	100

*They represent area equivalents, because intensification provides additional yields without occupying extra land.

response to the additional food demand. The final aggregated global area to supply the same amount of wheat resulted in more than 1 ha (precisely 1.2 ha, see Table 2), due to lower average yields around the world than Danish cropland. The new hybrid approach confirmed that induced deforestation GW impacts (TI, shown as iLUC_{food_TI}) are more important than GW impacts associated with DR impacts (iLUC_{food_DR}) and the dominant factor inside the iLUC figure (82% of iLUC_{food}, see Table 2). The compendium of the region-specific results of iLUC_{food} is shown in Table 3. There we see that, within the TI, the regions and biomes that contribute mostly to iLUC_{food_TI} (and thus to iLUC_{food}) are the tropical rainforest conversions in Brazil and sub-Saharan Africa. Induced deforestation there alone makes up more than half of the total iLUC_{food} emissions (30% and 25%, respectively), although only 13% and 22% of the induced LUC area-wise occurs. Most of the induced iLUC_{food} occurs in EU regions (31% of total area expansion), but these contribute only with 11% of its GHG emissions. This is largely due to the difference between DR – which is the dominating consequence in the EU regions, and TI – which is dominating in tropical regions. Our model demonstrates its ability to capture these important differences in induced LUC patterns. Likewise, this puts in sharp contrast the different GW implications that continuing land occupation (as DR) and induced land transformation (TI) have, which can be observed in the calculated CFs in Table 3.

iLUC_{feed}. When occupying one ha of marginal grassland in Denmark for energy cropping, the resulting global aggregated area to supply that new feed demand is lower (0.93 ha_{dem} ha⁻¹_{occup}), 37% of which is truly new area (the rest is intensified agricultural area). This is

because intensive agro-industrial fields (for soya and maize) are more productive than extensive pastures (i.e. they need less land to produce same amount of proteins and energy). Interestingly, also in the biophysical approach, most GHG emissions from the iLUC_{feed} factor came from induced deforestation (80%), even if a different approach and different intensification–expansion shares were considered. The presented results confirm that agricultural area expansion GW impacts are the most concerning ones (between 93% and 80% of the total iLUC emissions), regardless the approach followed to model iLUC (see Table 2).

Environmental performance of SRC willow

The results depicted in Fig. 2 show the main contributors to the GW potential impact of the different gasification willow bioenergy systems. GW impacts from farming activities are roughly compensated by the biochar amendment process (permanent C sequestration) in all scenarios. As a result of the low-input agriculture adopted, GW impacts from NPK fertilizer production are negligible (not visible in Fig. 2). Similarly, woodchip transportation is also negligible. The GW impact of CHP (Gasification) is neutral in itself, as the emitted C was previously captured by willow through photosynthesis (temporary C sequestration). Incurred GW impact from induced iLUC_{food} is approximately compensated by the avoided natural gas consumption for CHP in the arable land scenario. As a result, gasification of willow from arable land remains roughly carbon neutral after the 20-year cycle. On the other hand, iLUC_{feed} and dLUC emissions for the marginal grassland and marginal abandoned land scenarios are significantly lower than iLUC_{food} in the arable land scenario. GHG emission savings achieved from the avoided natural gas combustion made SRC willow from both of the marginal land scenarios a carbon sequestering energy system. For these two last scenarios, predicted changes in SOC (depicted inside dLUC in Fig. 2) were minor from a life-cycle point of view – BioC made up most of the dLUC effect (97%) shown in the marginal abandoned scenario.

As it can be read in Table 4, gasification cogeneration from willow grown on marginal land has a potential negative GW impact, while willow from arable land remains roughly neutral. For the rest of impact categories assessed, there was little difference between the scenarios (see Table 4). As the soil type and modelled land management were the same for both marginal scenarios, they had same nutrient leaching and same yield, which translated into the same eutrophication, acidification and toxicity impacts per hectare (Table 4) and per megajoule energy provided (Table 5). Interestingly,

Table 3 Data and calculated CFs for iLUC_{food_area} emissions (the economic part of the hybrid model). Area expansion (A_{iLUC}) by geographical region (aus: Australia; xme: Middle East & North Africa; can: Canada; usa: USA; xla: Latin America (excl. Brazil & Peru); bra: Brazil; xeu15: EU 15; xss: sub-Saharan Africa; row: rest of the world) as given by Kløverpris (2008). 'Land cover 1' and 'Land cover 2' refer to the initial and final land covers. Affected biomes adapted from Kløverpris (2008) to fit into UNEP-SETAC recommended classification of Olson *et al.* (2001). The land transformation process is reversed wherever historical land abandonment was identified, implying a DR impact. A_{iLUC} is given in 10^{-4} ha_{exp} (Mg wheat)⁻¹, carbon stocks (BioC, SOC) and CFs in Mg C ha_{exp}⁻¹ and natural relaxation times (T_{relax}) in years (NR: not relevant; *changed from 74 to 110; † a duration factor of 0.779 was applied). TI and DR given in Mg CO₂ ha_{occup}⁻¹. Annualized iLUC factors and total iLUC_{food_area} in kg CO₂ ha_{occup}⁻¹ yr⁻¹. All calculations and details can be found in Appendix S4.

Region	Land cover 1	Land cover 2	Affected biome(s)	A_{iLUC}	BioC	SOC	CF _{transf}	CF _{occup}	T_{relax}	TI	DR
aus	Shrub land/Forest	Arable	Temperate (savannah)/Mediterranean	74.3	28.3	80	45.3	0	NR	8.9	0
aus	Shrub land/Forest	Pasture/meadow	Temperate (savannah)/Mediterranean	32.7	28.3	80	21.3	0	NR	1.9	0
aus	Pasture/meadow (DR)	Shrub land/ Grassland	Xeric shrubland/Temperate grassland	37.0	6.5	30	0	Neglig.	NR	0	Neglig.
xme	Pasture/meadow	Arable	Mediterranean forest/Xeric shrubland	32.4	7	80	24.0	0	NR	2.1	0
xme	Shrub land/Forest	Arable	Mediterranean forest/Xeric shrubland	33.9	24.8	80	41.8	0	NR	3.8	0
can	Pasture/meadow	Arable	Boreal forest/Taiga	8.6	7	300	79.0	0	NR	1.8	0
can	Arable (DR)	Forest	Boreal forest/Taiga	96.8	65.3	300	0	11.5	238	0	3.0
can	Pasture/meadow (DR)	Forest	Boreal forest/Taiga	10.0	65.3	300	0	8.8	133	0	0.2
usa	Pasture/meadow	Arable	Temp. grassland/Temp. forest	80.2	7	120	34.0	0	NR	7.2	0
usa	Pasture/meadow (DR)	Shrub land	Xeric shrubland	67.9	3	30	0	Neglig.	NR	0	Neglig.
xla	Shrub land	Pasture/meadow	Tropical savannah/temperate grassland	6.9	18	40	11.0	0	NR	0.2	0
xla	Forest/Shrub land	Arable	Tropical savannah/tropical forest	63.6	98	80	115.0	0	NR	19.5	0
xla	Pasture/meadow (DR)	Grassland	Temperate grassland (<i>pampa</i>)	16.5	10	40	0	Neglig.	NR	0	Neglig.
bra	Shrub land/Forest	Pasture/meadow	Mediterranean forest (<i>cerrado</i>)	41.2	46.6	80	39.6	0	NR	4.3	0
bra	Forest	Arable	Tropical moist forest	91.7	170	120	197.0	0	NR	48.0	0
bra	Forest	Pasture/meadow	Tropical moist forest	84.4	170	120	163.0	0	NR	36.6	0
xeu15	Pasture/meadow	Arable	Temperate Broadleaf & Mixed	147.3	7	100	29.0	0	NR	11.4	0
xeu15	Arable (DR)	Forest	Temperate Broadleaf & Mixed	227.6	130	140	0	29.5	110*	0	17.8
xeu15	Pasture/meadow (DR)	Forest	Mediterranean forest	133.3	46.6	100	0	10.7	74†	0	3.0
xss	Pasture/meadow	Arable	Temp. grassland/Temp. forest	61.3	7	150	41.5	0	NR	6.8	0
xss	Arable (DR)	Grassland	Temperate grassland (<i>steppe</i>)	91.0	10	60	0	4.0	110	0	1.0
xss	Pasture/meadow (DR)	Forest	Temperate Broadleaf & Mixed	90.5	130	140	0	33.2	74†	0	6.2
xss	Forest/Shrub land	Arable	Tropical savannah/tropical forest	167.6	86.5	90	106.0	0	NR	47.2	0
xss	Forest/Shrub land	Pasture/meadow	Tropical savannah/tropical forest	117.2	86.5	90	79.5	0	NR	24.8	0
xss	Shrub land	Pasture/meadow	Xeric shrubland	81.3	3	20	0.0	0	NR	0.0	0
row	Unknown	Unknown	Unknown	91.1	50.5	111	36.5	0	NR	8.8	0
Subtotal				1656.4						234.3	31.2
Annualized iLUC factors										11714.7	1559.5
Total iLUC _{food_area}										13274.2	

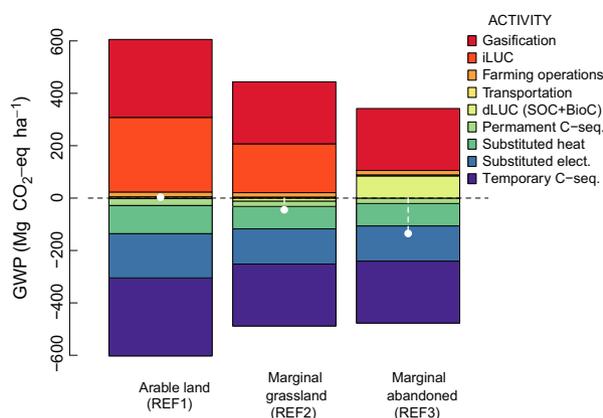


Fig. 2 Contribution to GW potential impacts per life-cycle activity. White dots show the net GW impact for each scenario (quantitative results in Table 4). Carbon sequestration and avoided fossil emissions from substituted heat and electricity generation are shown as negative GW impacts.

Denmark would benefit from a low-input management that SRC willow entails (three times less input of N than common land management), if arable land is taken for willow cropping. This is because previous intensive wheat cultivation is temporarily displaced (for a period equal to $T_{\text{occup}} = 20$ years) abroad in the form of world-spread regional impacts. If marginal land is cultivated though, an increased regional burden in eutrophication and toxicity will follow as no fertilization or pesticide was previously applied on those lands. Worldwide aggregated figures remain nevertheless similar for all the assessed scenarios.

In order to compare to the fossil fuel alternatives, the environmental impact scores are expressed relative to the energy output in Table 5. When compared to natural gas, all gasification willow bioenergy scenarios outperform the fossil fuel reference for all impact categories, except the eutrophication impact category.

Sensitivity and uncertainty analysis

To investigate the reliability of the results, a sensitivity and uncertainty analysis was performed. Parameter and scenario uncertainties were addressed, the former arising from the quality of input data, while the latter being inherent to the modelling choices (i.e. the modelling approach, system boundaries and assumptions made). The substituted energy source, the displaced crop and the assumed intensification–expansion shares were changed to quantify the sensitivity of the simulation results to these key assumptions (i.e. scenario uncertainty analysis). When the substituted energy is changed, all willow scenarios outperform coal-based CHP in acidification and GW by 1 and 2 orders of magnitude,

respectively (see Table 5). If barley was assumed to be the crop displaced instead of wheat, the GW impact of the arable scenario is also significantly reduced, leaving it in the range of the marginal grassland scenario. When global averages were used for the intensification–expansion processes in food production (as in $iLUC_{\text{feed}}$), $iLUC_{\text{food}}$ decreased by 37%, which brought the relative GW of the arable land scenario down to that of the marginal abandoned land scenario. The scenario uncertainties assessed did not invalidate, but rather confirm that SRC willow is overall environmentally preferable than any fossil fuel alternative. A parameter sensitivity analysis was performed for the parameters which potentially can influence the results significantly (from the contribution analysis depicted in Fig. 2). After this, the $iLUC$ factors and yield figures were identified as the most critical ones for the LCA results (see Table 6 for the sensitivity results of selected key parameters).

A Monte Carlo analysis (10 000 runs) was finally carried out for the quantification of parameter uncertainties. An exhaustive list of all the included parameters with their confidence intervals can be seen in Appendix S6, while the resulting uncertainties are shown in Fig. 3. Analysed parameter uncertainties did not change the main reading of the results.

Discussion

The specific roles of land and LUC in the sustainability of energy cropping

Here we discuss the key land-use aspects that could not be covered in the uncertainty analysis and which may put into question the sustainability of a gasification willow bioenergy system because of the assumptions, system boundaries and approach taken in the study.

dLUC emissions as foregone C sequestration. Although the C emissions from dLUC presented are not directly emanating from the assessed land (as the dLUC concept would suggest), they do represent a C sink opportunity loss –or foregone C sequestration (Koponen & Soimakallio, 2015). This is similar to the crediting of ‘avoided fossil emissions’ in LCAs of renewable energy systems, where these are accounted negatively, even though they are not factual carbon sinks. The lost C sequestration opportunity is thus considered as a CO₂ emission from occupying abandoned land (BioC being the most significant) and hence included inside the dLUC emissions. Short-term C budgets of grassland succession into shrublands may not be fully clear (Jackson *et al.*, 2002), but long-term C dynamics of natural regeneration on open land consistently show higher stocks of BioC (Schulze *et al.*, 2004) and SOC (Don *et al.*, 2011). The

Table 4 Environmental impacts of gasification-CHP per hectare of willow cultivated on different Danish land types for the four selected impact categories

Energy system	GW ₁₀₀ (kg CO ₂ -eq ha _{occup} ⁻¹)	Eutrophication (kg PO ₄ ³⁻ -eq ha _{occup} ⁻¹)	Acidification (kg SO ₂ -eq ha _{occup} ⁻¹)	Toxicity (kg DCB-eq ha _{occup} ⁻¹)
CHP willow (arable)	4047	124	156	2.2 × 10 ⁷
CHP willow (marginal grassland)	-43 745	124	138	2.6 × 10 ⁷
CHP willow (marginal abandoned)	-134 296	124	138	2.6 × 10 ⁷

Table 5 Environmental impact per energy output for willow-based gasification-CHP. SRC willow grown on different Danish land types and for the fossil fuels that it may replace, for the four selected impact categories. Note that the impacts shown for CHP willow are credited with the substituted NG.

Energy system	GW ₁₀₀ (g CO ₂ -eq MJ ⁻¹)	Eutrophication (mg PO ₄ ³⁻ -eq MJ ⁻¹)	Acidification (mg SO ₂ -eq MJ ⁻¹)	Toxicity (g DCB-eq MJ ⁻¹)
CHP willow (arable)	0.8	23.2	29.1	409.6
CHP willow (marginal grassland)	-10.4	29.1	32.4	611.9
CHP willow (marginal abandoned)	-31.8	29.1	32.4	611.9
CHP fossil fuel (natural gas)	75.2	14.9	85.3	739.5
CHP fossil fuel (coal)	108.0	20.7	308.1	739.5

Table 6 Scenario and parameter uncertainty analysis for quantification of result's sensitivity to key choices and parameters

	Change	GW ₁₀₀ (g CO ₂ -eq MJ ⁻¹)			GW ₁₀₀ change (%)		
		Arable	Marginal grassland	Marginal abandoned	Arable	Marginal grassland	Marginal abandoned
Scenario uncertainty analysis							
Marginal energy (coal)	Assumption	-131.0	-153.6	-197.0	-8595%	-632%	-206%
Marginal crop (barley)	Assumption	-25.7	-	-	-1768%	-	-
Intensification-Expansion shares (global averages)	Approach*	-38.1	-	-	-2569%	-	-
Parameter sensitivity analysis							
iLUC	+10%	6.1	-6.0	-	703%	43%	-
SOC_gain	+10%	0.7	-10.6	-31.9	5%	-3%	0%
BioC_gain_REF3	+10%	-	-	-29.9	-	-	6%
Yield	+10%	-4.8	-16.0	-37.4	735%	-54%	-18%
N ₂ O emissions	+10%	1.0	-10.2	-31.6	-25%	2%	1%
Electric efficiency	+5%	-0.7	-11.8	-33.3	-190%	-14%	-5%
Low heating value (LHV)	+5%	-2.1	-13.3	-34.7	-380%	-28%	-9%

*The original shares as given by Kløverpris (2008) (30–70%, respectively) were changed within the iLUC_{food} hybrid model to global average shares (as in the biophysical approach, 63–37%, respectively).

applied foregone C sequestration of willow grown on abandoned land is 1.15 Mg C ha_{occup}⁻¹ yr⁻¹, which is close to the average figure of 1 Mg C ha_{occup}⁻¹ yr⁻¹ reported by Koponen & Soimakallio (2015).

iLUC in literature. Despite the uncertainty of iLUC effects and their variability among literature, it is widely accepted that their contribution to the life-cycle impacts of dedicated biofuels is, almost with full certainty,

nonzero; likely, rather significant (Edwards & Mulligan, 2010; Lapola *et al.*, 2010; Broch *et al.*, 2013; Ahlgren & Di Lucia, 2014; Plevin *et al.*, 2015). Thus, ignoring them is not acceptable (Hertel *et al.*, 2010; EEA, 2011; Sanchez *et al.*, 2012; Muñoz *et al.*, 2014). Also, the latest EU directive on renewable energy has amended the text from 2009 to include, among other things, the 'significant GHG emissions linked to iLUC', 'given that current biofuels are mainly produced from crops grown on

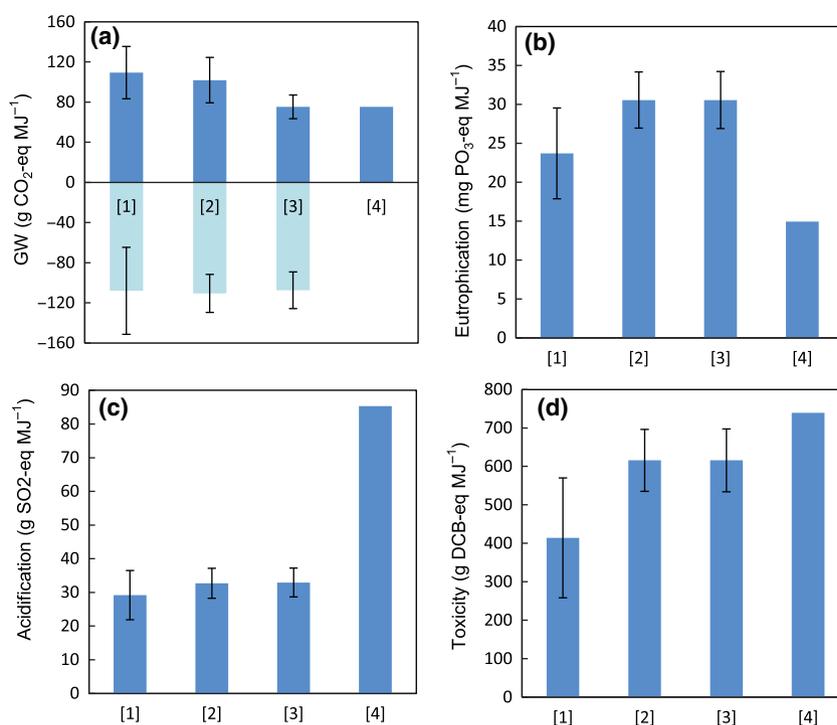


Fig. 3 Mean values of potential environmental impacts (shown per MJ, for comparison with the fossil fuel reference) for gasification willow grown on [1] Arable land, [2] Marginal extensive grassland, [3] Marginal abandoned farmland and the fossil reference [4] Natural Gas. Selected impact categories shown: (a) global warming, (b) eutrophication, (c) acidification and (d) toxicity. Depicted error bars represent the confidence intervals (95% or 4σ) after Monte Carlo simulation. Uncertainty results in GW are disaggregated as provided by GABI software (emissions: positive; sequestration/emission-avoidance: negative).

existing agricultural land' (European Union, 2015). Comparing iLUC figures is difficult, as many different assumptions are involved in the modelling. However, we may consider the nonannualized iLUC emissions per occupied area, as these are independent of the predicted yields of biofuel crops and the amortization period used. Doing so, we get that our factor ($iLUC_{\text{food}} = 265.5 \text{ Mg CO}_2 \text{ ha}_{\text{occup}}^{-1}$) is similar to other published economic iLUC factors (from Table 2, Corn ethanol results, in Broch *et al.*, 2013): $277 \text{ Mg CO}_2 \text{ ha}_{\text{occup}}^{-1}$ (by Tyner *et al.*, 2010), $244 \text{ Mg CO}_2 \text{ ha}_{\text{occup}}^{-1}$ (by CARB-LCFS) and $242 \text{ Mg CO}_2 \text{ ha}_{\text{occup}}^{-1}$ (by FAPRI-Internat'l).

The biophysical $iLUC_{\text{feed}}$ figure ($159 \text{ Mg CO}_2 \text{ ha}_{\text{occup}}^{-1}$) lies in the low-end range of the emission factors analysed in Broch *et al.*, 2013. Not surprisingly, it remains around 3 times higher than other biophysical iLUC 'discounted' factors (Schmidt *et al.*, 2015; Tonini *et al.*, 2015). This big divergence is, however, due to different reference land uses adopted by these authors when accounting for the GHG emissions from land transformation (Klöverpris & Mueller, 2012). Even though such discrepancies have not found an optimal solution yet, assuming agricultural expansion as a dynamic land-use

baseline to account for induced deforestation impacts seems like assuming ongoing global fossil emissions as a dynamic baseline to account for GHG impacts from additional fossil combustion. In this regard, we believe that the applied reference land-use framework (Table 1) along the assessment ensures the consistency needed to get iLUC figures from different studies converge to a narrower range of results.

Marginal lands: concepts, misconceptions and future prospects. Marginal lands have been focus of attention as they are purportedly able to avoid undesirable iLUC effects. Nevertheless, abandoned farmland in Europe may be the most suitable marginal land type for sustainable bioenergy production, following the extensive review by Dauber *et al.*, 2012. A genuine challenge comes along with them, as these lands rapidly change their use (or nonuse), adapting to new owners' needs, new crop breeds, market signals and policies on place (Pointereau *et al.*, 2008; Terres *et al.*, 2013). In 2008, Spain, Poland and France alone were estimated to have 3.3 million ha of abandoned land (Pointereau *et al.*, 2008) and these are expected to increase across EU in the future (Terres *et al.*, 2013). With the right

incentives and policies, energy cropping on these lands coupled to gasification can significantly help achieve EU's energy goals without iLUC effects, while sequestering substantial amounts of carbon. Assuming same conditions as in this study, low-input willow cropping with gasification would be able to produce 37 TWh_{el} yr⁻¹ of decentralized power and 58 TWh_{th} yr⁻¹ of district heating, sequestering an average of 22 Tg CO₂-eq yr⁻¹, only with the abandoned lands of these three countries.

Denmark has no statistics on abandoned land and is a country with intensively cultivated agricultural land. Thus, marginal extensive grasslands seem the only land resource that may increase the country's bioenergy potential. However, if some of these pastures are intended to grow SRC like willow, some national policies to reduce the demand of land-intensive products would need to accompany the process in order to avoid undesirable iLUC effects. In 2014, there were in Denmark around 197 500 ha of permanent pasturelands (Statistics Denmark, Copenhagen, 2015; www.dst.dk). If, say, one quarter of those marginal grasslands were released from their current use and demand, 159 Gg CO₂-eq yr⁻¹ could be additionally sequestered, providing 815 GWh_{el} yr⁻¹ of power and 1.3 TWh_{th} yr⁻¹ of district heating.

Other environmental aspects

This assessment so far excluded potentially crucial impacts on biodiversity which may question the findings of this study (UNEP, 2009).

Energy cropping on arable land may induce transformation of large land areas (around 0.88 ha_{exp} ha_{occup}⁻¹; see Table 2). Energy cropping in marginal grasslands can have similar effects (0.34 ha_{exp} ha_{occup}⁻¹). In our iLUC_{food} model, we estimate that around 30% of the expansion (or 0.37 ha_{exp} ha_{occup}⁻¹) may occur at the expense of virgin ecosystems with high biodiversity (tropical rainforests) (see Table 3). The species richness of such forests is around one order of magnitude higher than other ecosystems (Schmidt, 2008). As for the severity of that impact, those ecosystems are known to host many endemic species, whereby their loss can be considered irreversible (IUCN, 2013). On the other hand, SRC can potentially benefit farm-scale biodiversity (positive dLUC impacts), enriching landscape's structural heterogeneity if planted not as landscape-wide monoculture but in smaller plots under low-input agricultural systems (Dauber *et al.*, 2010; Rowe *et al.*, 2011). The positive effect of a SRC plantation on biodiversity will however depend on the specific surroundings of the location (MacDonald *et al.*, 2000; Rey Benayas, 2007) (see Table 7).

Regarding marginal lands, preventing the abandonment and intensification of semi-natural habitats as extensive grasslands is beheld as a key action to halt the decline of biodiversity in Europe (EEA, 2009; European Union 2013). Nevertheless, the promotion of regional biodiversity does not increase the global genetic pool (which should be regarded as the final target worth protecting), while negative iLUC impacts on biodiversity may decrease this pool if endemic endangered species are affected. This is particularly relevant from a global viewpoint, as global (not local) biodiversity loss rate is the most concerning of the already crossed planetary boundaries (Rockström *et al.*, 2009).

Key learnings

Carbon negative bioenergy is urgently needed in the light of pressing climate change and mitigation binding accords like the international agreement at the COP21 meeting in Paris 2015. The combination of low-input agriculture with high-yielding, locally-adapted willow cultivars grown in marginal land with efficient gasification technology and biochar amendment made our bioenergy system perform significantly better, environmentally speaking, than other published assessments of similar crops. Biochar amendment resulted to be a significant factor for carbon neutrality or sequestration as compensation for fossil C emissions in the transportation and farming stages. Furthermore, it involves nutrient recycling and may help improve the quality and sustainability of agricultural soils.

When adopting multiple land-use references and keeping consistency along their implementation, diverse iLUC and dLUC effects arise which have different environmental implications. The adopted hybrid modelling approach to estimate the iLUC emissions from energy cropping in arable land was developed to capture the different contributions from land transformation (TI), delayed relaxation (DR) and intensification impacts. Out of these three basic iLUC effects, induced deforestation or TI resulted to be of highest concern. It summed up to 82% of the GW impacts from iLUC_{food}, triggering 0.88 ha_{exp} ha_{occup}⁻¹, or 0.34 ha_{exp} ha_{occup}⁻¹ when a biophysical

Table 7 Qualitative assessment of biodiversity effects from changing assessed land uses to SRC willow. These are divided among dLUC and iLUC effects (+ denotes a positive effect, – and – – negative and strongly negative effect, 0 is no effect)

	dLUC	iLUC
Arable land	+	– –
Marginal extensive grassland	+/-	– –
Marginal abandoned land	+/-	0

modelling approach (iLUC_{feed}) was taken. The characterization factors (CFs) developed differentiated between occupation (as DR impacts) and transformation (as induced deforestation impacts). These CFs consistently showed a higher GW impact per ha_{exp} for the CF_{transf} (see Table 3). All this emphasizes the importance of incentivizing energy cropping on abandoned farmland (or land at risk of abandonment) in EU, which can also help tackle the long rural depopulation problem that different European Common Agricultural Policy (CAP) frameworks have tried to reverse.

Consequently, using marginal abandoned land showed to be the most environmentally sound option (−31.8 g CO₂-eq MJ^{−1}), especially when considering the additional potential impacts on biodiversity. DR impacts (4116 kg CO₂-eq ha^{−1}_{occup} yr^{−1}) in abandoned farmland can be regarded as the ‘trade-off price’ that iLUC-free (thus protecting biodiversity-rich tropical areas) bioenergy needs to pay. On the other hand, marginal extensive grasslands could be a good alternative for energy cropping (−10.4 g CO₂-eq MJ^{−1}) in countries like Denmark where abandoned farmland may be inexistent. Although with a potential negative impact on biodiversity, the use of these lands could be a compromise solution between using arable land and the elusive land at risk of abandonment. If the bioenergy potential of Denmark wants to be substantially increased without undesirable iLUC effects, part of these extensive grasslands ought to be progressively released from their current use. This calls for coordinated action from national and European governments, setting clear guidelines and policies on place that can give the right incentives both to farmers and citizens.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Appendix S1. Life cycle inventory of farming operations and gasification process.

Appendix S2. Soil sampling.

Appendix S3. dLUC model for abandoned land: continued occupation with dynamic reference land-use.

Appendix S4. iLUC model for marginal grassland (iLUC_{feed}).

Appendix S5. iLUC model for arable land (iLUC_{food}): a hybrid approach to include transformation, occupation and intensification impacts.

Appendix S6. Sensitivity and uncertainty analysis.