Climate regulation, energy provisioning and water purification: quantifying ecosystem service delivery of bioenergy willow grown on riparian buffer zones using life cycle assessment

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Abstract

Whilst life cycle assessment (LCA) boundaries are expanded to account for negative indirect consequences of bioenergy such as indirect land use change (ILUC), ecosystem services such as water purification sometimes delivered by perennial bioenergy crops are typically neglected in LCA studies. Consequential LCA was applied to evaluate the significance of nutrient interception and retention on the environmental balance of unfertilised energy-willow planted on 50 m riparian buffer strips and drainage filtration zones in the Skåne region of Sweden. Excluding possible ILUC effects and considering oil-heat substitution, strategically planted filter willow can achieve net global warming potential (GWP) and eutrophication potential (EP) savings of up to 11.9 Mg CO_2e and 47 kg PO_4e ha^{-1} yr^{-1}, respectively, compared with a GWP saving of 14.8 Mg CO_2e ha^{-1} yr^{-1} and an EP increase of 7 kg PO_4e ha^{-1} yr^{-1} for fertilised willow. Planting willow on appropriate buffer and filter zones throughout Skåne could avoid 626 Mg yr^{-1} PO_4e nutrient loading to waters.

Keywords: LCA, eutrophication, greenhouse gas emissions, bioenergy, agriculture, environment

Available online at: http://link.springer.com/article/10.1007%2Fs13280-016-0790-9
DOI: 10.1007/s13280-016-0790-9

Introduction

Willow as a bioenergy feedstock

Short rotation coppice (SRC) willow is a relatively low-input perennial bioenergy feedstock that can contribute to European renewable energy and GHG emission reduction targets (Fischer et al., 2007; EC, 2009). Sikkema et al. (2011) project that SRC energy plantations could supply up to 300 Tg of biomass and 4.41 EJ energy across the EU27, although there remain considerable socio-economic and policy barriers to deployment on such a scale (Sluka and Peck, 2015). Wide spread cultivation of willow and other SRC feedstocks would lead to significant landscape scale effects on ecosystem services, which are context (site) dependent and poorly quantified. Börjesson (1999) highlighted a wide range of positive environmental effects, especially water purification via nutrient buffering, that could be realised by strategic planting of willow in Sweden. In this paper, we evaluate the potential significance of such nutrient buffering effects within a quantitative life cycle assessment (LCA) framework.

Bioenergy and food production

The sustainability of bioenergy feedstock production is increasingly assessed with respect to implications for sustainable food production (Godfray et al., 2010). Projected increases in demand for agricultural commodities suggest a need to “spare” non-farmed high nature value areas from agricultural expansion via “sustainable intensification” (Garnett et al., 2013). Although current intensive crop and livestock systems may produce food with a lower GHG intensity than extensive systems when global land use change (LUC) is considered (Burney et al., 2010; Havlík et al., 2014), such systems diminish the delivery of other ecosystem services (Haas, 2000; Firbank et al., 2013), especially via large releases of reactive nitrogen to air and water (Dalgaard et al., 2012; Pinder et al., 2012) that can be particularly problematic in the vicinity of large, enclosed water bodies. Kiedrzyńska et al. (2014) found strong positive correlations between sub-catchment agricultural intensity indicators and nutrient loads to the Baltic Sea.

Thus, the appropriation of agricultural land for bioenergy feedstock production can indirectly incur negative environmental effects through intensification or expansion of agricultural production elsewhere to compensate for lost food output. Such effects are captured in consequential LCA (CLCA) that is increasingly being applied to evaluate bioenergy interventions (e.g. Rehl et al., 2012; Tonini et al., 2012; Vázquez-Rowe et al., 2014; Styles et al., 2015; Styles et al., 2016). CLCA expands system boundaries to account for marginal effects induced by market signals arising from system modifications. Indirect effects such as indirect LUC (ILUC) are uncertain, but can outweigh benefits such as avoided GHG emissions from fossil energy substiution (Tonini et al., 2012). Despite recent efforts at standardisation (Weidema et al., 2009), Zamagni et al. (2012) note that boundaries applied in CLCA studies are somewhat arbitrary. A focus on marginal effects associated with displaced food production has led to an emphasis on ILUC and intensification within CLCA accounting (Kløverpris et al., 2008; Mulligan et al., 2010). Less attention has been paid to possible direct and indirect agronomic and landscape effects arising from low-input perennial bioenergy crops, which include buffering of nutrient losses to water courses.

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Nutrient buffering

Methodological simplifications predispose CLCA studies to overlook potentially positive environmental consequences that may arise in certain landscape contexts, as identified using a wider ecosystem approach (Valentine et al., 2012; Bennett et al., 2014). Trees and other low-input perennial bioenergy feedstock planted within agricultural landscapes have the potential to regulate water flow rates and nutrient transfer from soil to water, and also to reduce soil erosion and wind damage (Bennett et al., 2014; Carsan et al., 2014). Default emission factors for nitrate leaching, phosphorus runoff and ammonia volatilization used in LCA studies are typically not calibrated to landscape-context-dependent hydrological and nutrient cycling parameters (Arbault et al., 2014). Thus, whilst LCA is invaluable for comparing the environmental efficiency of food and bioenergy supply chains, it has so far been of limited use to evaluate and inform spatially explicit strategies for sustainable bioenergy deployment – a task increasingly addressed using the ecosystem approach (Maskell et al., 2013) that may neglect important upstream and downstream indirect effects.

Aims and objectives

The overarching aim of this work is to demonstrate how the possible water purification effect of willow cultivation can be quantitatively represented in LCA, and the significance of doing so on the overall environmental balance of bioenergy willow. Specific objectives of this paper are to: (i) demonstrate how the water purification (nutrient retention) effect of willow can be incorporated into CLCA; (ii) compare the environmental balance of unfertilised willow planted on buffer strips and filter zones with fertilised willow; (iii) evaluate the potential for strategically planted willow to reduce eutrophication at the landscape scale within the Skåne region of Sweden – a major source of eutrophication in the Baltic Sea (Kiedrzyńska et al., 2014).

Materials and methods

Skåne regional scenarios

Skåne is a lowland agricultural region of southern Sweden, with a total area of 1,096,881 ha (Table S1.1). The total stream length in Skåne is 4106 km, with a further 1276 km of lake perimeter (SCB, 2014). This translates into a theoretical maximum riparian buffer area of 47,422 ha assuming 50 m buffer zone width (Börjesson and Berndes, 2006). Currently, agri-environmental payments for buffer zones amount to 3.437 M SEK, which translates to an area of between 1,146 and 3,437 ha at payment rates that vary between 1000 and 3000 SEK ha^{-1} yr^{-1} (Jordbruksverket, 2014a). Thus, there is considerable potential to expand buffer zones in Skåne. In this paper, we consider the introduction of new willow buffer and filter zones on the 434,506 ha of arable land in Skåne (SCB, 2014).

The theoretical maximum area of willow buffer strips in the agricultural landscape is determined by the occurrence of open waterways and the amount of arable land that lacks covered-drain systems. An estimation by Börjesson et al. (2002) is that the maximum area of buffer strips in Skåne amount to approximately 24,000 ha where nutrient-rich water from a runoff-generating area equivalent to some 140,000 ha can be treated. Of this area, roughly 40% could realistically be planted with willow, accounting for economic and policy barriers (Börjesson et al., 2002). The theoretical maximum area of arable land in Skåne where drainage water can be collected and used for irrigation has also been estimated at roughly 140,000 ha, which would require a willow vegetation filter area of

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approximately 32,000 ha to treat (Börjesson et al., 2002). The practical potential of willow vegetation filters is assumed to be restricted by physical factors, such as soil type, where sandy soils are more suitable than heavy clay soils, and the design and size of the covered-drain systems. The maximum area that could be established as willow vegetation filters in Skåne is estimated at around 20% of the theoretical area (Börjesson et al. 2002). Thus, a “water purification” scenario was defined based on establishment of 9600 ha of willow buffer strips and 6400 ha of willow filter zones located within the Skåne arable landscape (Figure 1). This water purification scenario was compared with a “yield maximisation scenario” in which the same total area of 16,000 ha was planted with fertilised willow, but none of this planting occurred adjacent to water courses and so did not give rise to any buffering or filtering effect via nutrient interception and retention (a simplified assumption to illustrate the magnitude of the buffering effect on environmental outcomes). The environmental balance of both these scenarios was expressed as *change* in environmental burdens compared with a simplified baseline situation in which average nutrient leaching factors were applied to the entire arable area, assuming negligible buffer strip area.

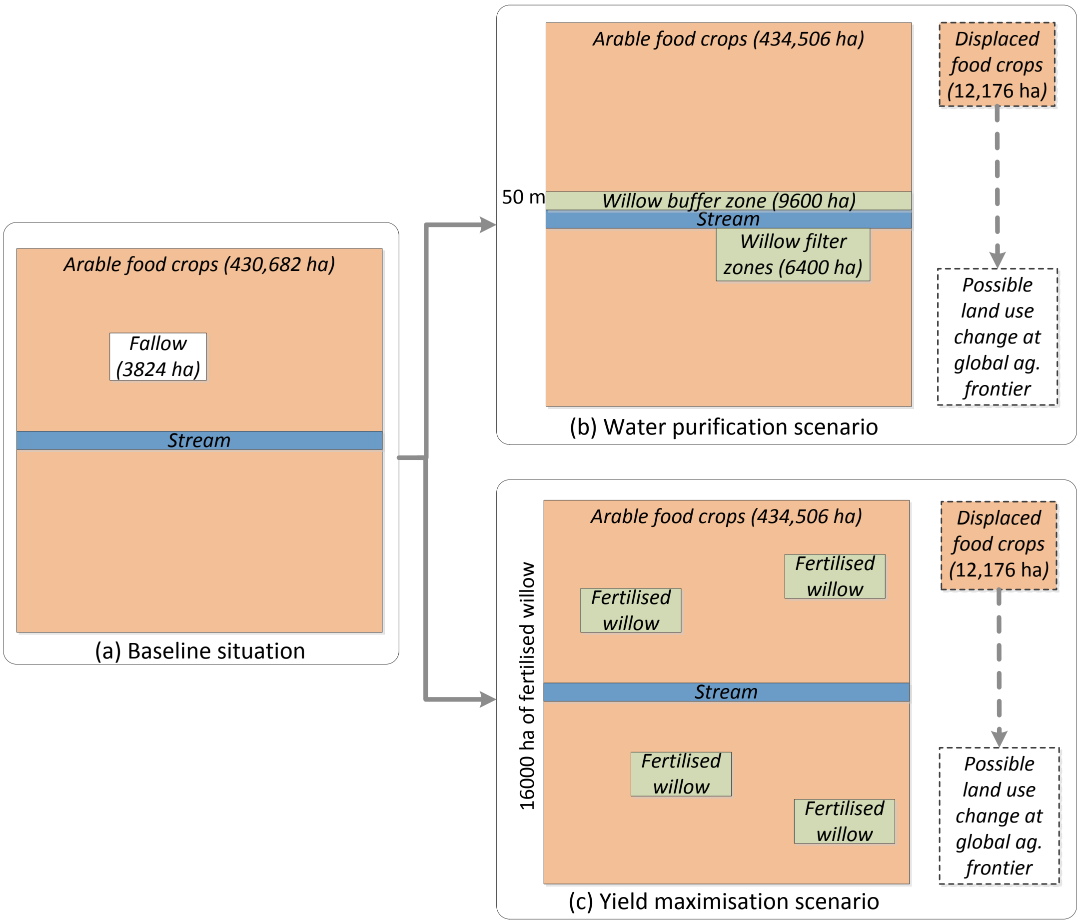

Figure 1. Simplified schematic representation of the water purification(b) and yield maximisation (c) scenarios in relation to the baseline situation (a) for Skåne arable land

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Life cycle assessment framework

The environmental balance of various willow cultivation strategies was evaluated based on attributional LCA (ALCA) of willow heat system burdens, and CLCA of environmental loading *changes* at the landscape scale, using an adapted version of the LCAD tool – essentially a farm model linked with LCA inventories nested within an expanded boundary CLCA framework (Styles et al., 2015a;b). ALCA boundaries included all direct system inputs from the technosphere, such as the manufacture and transport of all agrochemicals and diesel used in willow cultivation, all field emissions related to fertiliser and residue inputs, and transport and combustion of chipped willow to generate heat – but excluded the interception and retention of nutrient runoff from neighbouring fields which is regarded as a landscape-level change and thus captured in CLCA (Table 1). The ALCA functional unit is 1 MJ_{heat} output from a gasification boiler fired by chipped willow and operating at 90% conversion efficiency, based on a lower heating value of 18 MJ kg^{-1} dry matter (DM) wood, for comparison with burdens from an oil-heating reference system comprising a condensing oil boiler operating at 90% efficiency (Ecoinvent, 2014).

Table 1. Functional unit and factors considered in attributional and consequential life cycle assessment approaches

	Functional unit	Direct land use change	Food production dispacement	Possible indirect land use change	Nutrient interception & retention	Fossil fuel replacement
Attributional LCA	1 MJ_{th} useful heat output	Yes	No	No	No	No
Consequential LCA	One year of baseline arable food production	Yes	Yes	Yes	Yes	Yes

To calculate burden changes using CLCA, a simplified baseline situation of Skåne arable production was represented within the LCAD tool based on six major land use categories (Table 2), derived from SCB (2014) land use statistics and fertiliser application rates for Skåne (Jordbruksverket, 2014b).

Table 2. Field area, baseline nutrient requirements and yields for the six crop categories representing baseline arable food production in Skåne (CPP = crop protection products)

Crop category	Area ha	N	P_2O_5	K_2O kg ha^{-1} yr^{-1}	Lime	CPP	Diesel
Cereals	216,980	140	15	10	150	2.3	86.2
Arable grass ley	103,274	200	40	80	150		64.7
Oil seeds & legumes	56,850	130	20	17.5	150	1.2	99.3
Beets & potatoes	44,602	110	25	30	150	1.3	146.9
Other	8,977	145	25	34	150	1.2	99.3
Fallow	3,824	0	0	0	0	0	0

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Results were calculated and presented as *changes* in annual environmental loadings arising when land use shifts from the baseline situation to either the water purification or yield maximisation scenario (Figure 1), accounting for nutrient interception and retention effects. In order to consider displaced food production, the functional unit was one year of food production from 434,506 ha of arable land. It was assumed that 24% of the 16,000 ha of displaced food production moves to the current fallow area in Skåne, and the remainder is compensated for through either intensification on existing land or displacement of other agricultural production ultimately leading to agricultural expansion at the global agricultural frontier (Figure 1) (Styles et al., 2015b). The environmental intensity of displaced production was assumed to remain the same as for baseline production, except for possible additional ILUC burdens calculated from IPCC (2006) carbon and nitrogen fluxes associated with land transformation at the global agricultural frontier, accounted for over a 20-year transition period, as elaborated in S1.5. Uncertain ILUC burdens were expressed in relation to 0%, 50% and 100% of the maximum net area of Skåne food production displaced by willow cultivation, after subtracting the baseline fallow area (i.e. a maximum net ILUC area of 12,176 ha: Figure 1). New or avoided (counterfactual) processes were represented as environmental debits and credits relative to the baseline situation (Table 1).

Life cycle impact assessment was undertaken according to the CML (2010) method for acidification potential (AP), eutrophication potential (EP), fossil resource depletion potential (FRDP) and global warming potential (GWP) impact categories (supplementary information, S1.3). Emission factors for arable cultivation are largely taken from Styles et al. (2015a;b), and summarised in S1.2 and S1.4, respectively. Important data include GHG emission factors (IPCC, 2006), ammonia emission factors (Misselbrook et al., 2012), nutrient leaching factors updated for Sweden (Brandt et al., 2008; Johnsson et al., 2002; Withers, pers. comm., 2013) and process data from Ecoinvent v3.1 (Ecoinvent, 2014).

Scenario CLCA results were calculated at the regional level, but also presented per hectare appropriated for willow cultivation. Scenario results were normalised against annual environmental impact category loadings across the EU25+3 (Sleeswijk et al., 2008). ALCA results per MJ_{heat} were normalised against annual environmental loadings per capita, based on a population of 510 million within the EU28 (Eurostat, 2015).

Attributional LCA of willow heat

ALCA was undertaken for three types of willow cultivation: (i) “Fertilised willow”, where willow is planted on fertile areas away from water courses and fertilised to obtain maximum yields; (ii) “Buffer willow”, in which unfertilised willow is planted on riparian buffer zones and intercepts nutrient runoff from neighbouring arable land; (iii) “Filter willow”, in which willow is planted in a tile-drainage discharge zone, intercepting drainage from neighbouring arable production (Figure 1). Table 3 summarises key features for the different types of willow cultivation. Inputs were taken from González-García et al. (2012), including average annual diesel consumption for field operations of 24 kg ha^{-1}, herbicide application of 0.7 kg ha^{-1}, and a typical fertiliser-N application rate of 73 kg ha^{-1} (Aronsson et al., 2014). González-García et al. (2012) note that Swedish arable soils are sufficiently high in P and K that these nutrients are typically not applied to willow plantations. It was assumed

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that chipped willow is transported 50 km and combusted in a heating-boiler to replace oil heating, reflecting typical use of woodchip for district heating systems and farm heating in Skåne. Only N fertiliser was applied to Fertilised willow, with the same emissions factors as for N applied to food crops; i.e. 0.01 for direct N_2O-N, 0.02 for NH_3-N, 0.23 for NO_3-N, and 0.01 and 0.0075 for indirect N_2O-N from NH_3-N and NO_3-N, respectively.

Table 3. Important LCA parameters for the three types of willow cultivation

		Fertilised willow	Buffer willow	Filter willow
Fertiliser N[a]	Kg ha^{-1} yr^{-1}	73	0	0
Fertiliser P[b]		0	0	0
Fertiliser K[b]		0	0	0
Lime		0	0	0
Herbicides		0.7	0.7	0.7
Diesel		24	24	24
N retention[c,d]		0	70	100
P retention[c,d]		0	1.5	1.5
DM yield[b,d]	Mg ha^{-1} yr^{-1}	8.7	5.1	6.6

[a]Aronsson et al. (2014); [b]González-García et al. (2012); [c]Börjesson (1999); [d]Börjesson and Berndes (2006).

González-García et al. (2012) report average DM harvested yields of 6.7 and 3.9 Mg ha^{-1} yr^{-1} for fertilised and unfertilised willow plantations in Sweden, but this reflects use of older, lower-yielding willow varieties on less fertile soils (Dimitriou et al., 2011). Aronsson et al. (2014) reported yields of 5.9 and 10.8 Mg ha^{-1} yr^{-1} for unfertilised and fertilised modern willow varieties in field trials on typical Swedish arable soils. Considering these data, we conservatively estimated that modern willow varieties on typical Swedish arable soils could yield 30% more than older plantations on poorer soils reported in González-García et al. (2012), with fertilised and unfertilised DM yields of 8.7 and 5.1 Mg ha^{-1} yr^{-1} assumed for Buffer willow and Fertilised willow, respectively (Table 3). When Filter willow receives nutrient-rich drainage runoff water, yields are assumed to be 30% higher than unfertilised willow (Börjesson and Berndes, 2006), leading to a central DM yield estimate of 6.6 Mg ha^{-1} yr^{-1} for Filter willow. Yields were changed ±25% to explore the sensitivity of landscape scenario results.

When replacing annual arable crops, willow will also result in soil organic carbon (SOC) accumulation in the region of 0.5 Mg C ha^{-1} yr^{-1} (Börjesson, 1999; Matthews and Grogan, 2002) that is accounted for in ALCA (Table 1). Small annualised changes in above-ground and below-ground biomass were also calculated based on average standing biomass C compared with the default 5 Mg C ha^{-1} for arable crops (IPCC, 2006), and assuming a below-to-above ground biomass ratio of 33% (González-García et al., 2012).

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Consequential LCA of willow scenarios

Interception and retention of runoff and drainage nutrient losses from neighbouring crop production was considered in the CLCA as a change from the baseline situation (Table 3). It was assumed that unfertilised willow cultivation does not directly contribute any anthropogenic nutrient loading (no direct inputs from the technosphere), but instead intercepts nutrient losses from upstream areas before they reach water courses. The efficiency of nitrogen retention in willow buffer strips depends on water flow pathways controlling the transport of nutrients through the landscape, and the width of the buffer zone. About 70% of the water's N content is estimated to be removable in zones 25-50 m wide, amounting up to 70 kg N ha^{-1} yr^{-1}, provided that the willow plantation is harvested regularly to maintain nutrient uptake (Börjesson and Berndes, 2006) (Table 3). Thus, a 50 m wide willow buffer strip, where half of the width is harvested at a time, could provide a continuous high uptake of nutrients. A 50 m wide willow buffer zone can also retain 1.5 kg P ha^{-1} yr^{-1} (Börjesson, 1999). Börjesson (1999) report that 33% of the N retained in willow buffer strips is denitrified. According to a mass balance N cycle for European agriculture presented in PBL (2011), N_2O-N emissions represent 3% of N_2 emissions. Thus, for Buffer willow, it was assumed that 1% of N retained in willow buffer strips is emitted as N_2O-N, compared with a 0.75% N_2O-N emission factor for leached NO_3-N (IPCC, 2006) that finds its way into water bodies in the baseline situation.

Retention of nutrients from tile drain outflows was also considered for the CLCA of Filter willow, based on Börjesson and Berndes (2006). Nitrogen retention in willow vegetation filters irrigated by nutrient-rich drainage water is estimated to be, on average, 100 kg N ha^{-1} yr^{-1} (Table 3). Lindroth and Båth (1999) show that water deficiency is often a growth-limiting factor in willow cultivation, even in countries like Sweden with significant precipitation throughout the year. An estimation is that drainage water irrigation in willow vegetation filters in Skåne will increase the biomass yield by at 30% compared with average yields for well-managed, rain-fed willow plantations on good soils (Börjesson and Berndes, 2002) (Table 3). To explore the sensitivity of results to nutrient retention rates, nutrient retention rates for buffer and filter willow were changed ±50%.

Results

LCA results per hectare and MJ_{th}

Willow cultivation incurs relatively small environmental burdens per MJ of useful heat output (Figure 2). A lower energy yield per hectare means that the soil C sequestration credit, expressed as CO2e MJ_{th}^{-1}, is highest for Buffer willow despite lower soil C sequestration on a per hectare basis compared with higher yielding Filter and Fertilised willow (Figure 2). Normalisation indicates that fossil resource depletion is an environmental hotspot for oil heat, whilst eutrophication is a hotspot for willow heat, within the context of European environmental loadings (Figure 3). All types of willow cultivation lead to wood heat with substantially lower fossil resource depletion and global warming burdens compared with oil heat, and significantly lower acidification burdens (Figure 3). However, the eutrophication burden of heat generated from Fertilised willow is significantly greater than for oil heat.

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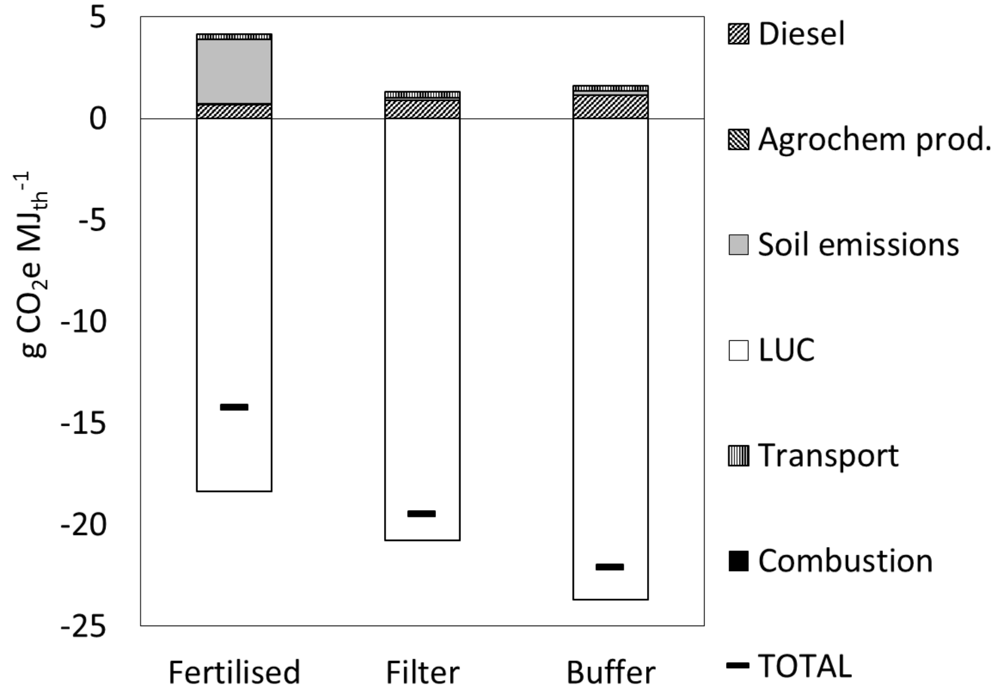

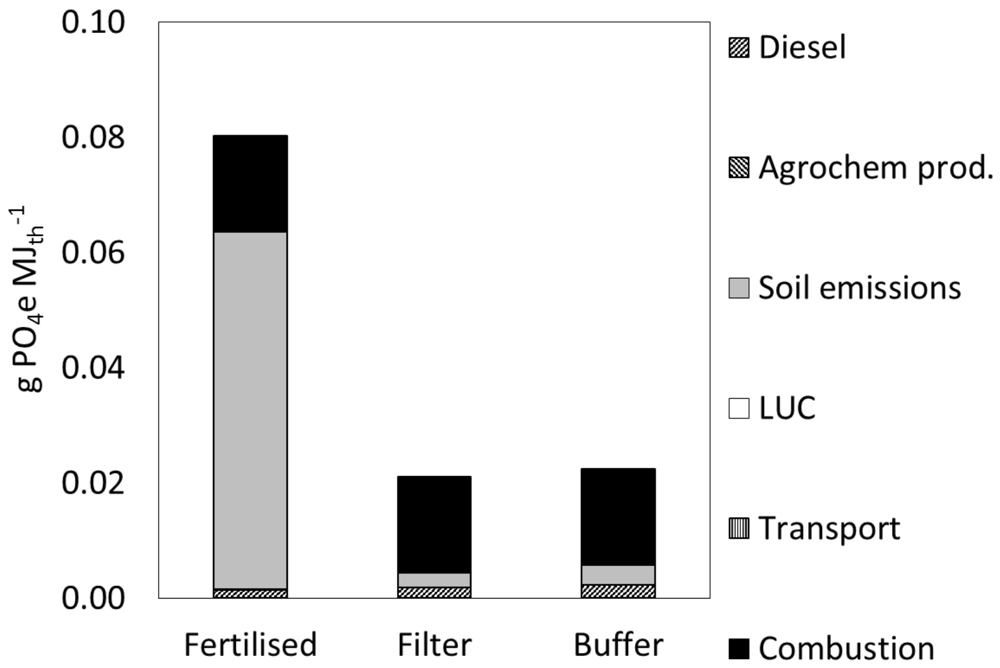

Figure 2. Contribution of major processes to the global warming (top) and eutrophication (below) burdens of 1 MJ_{th} of willow-sourced wood heat, calculated by attributional LCA

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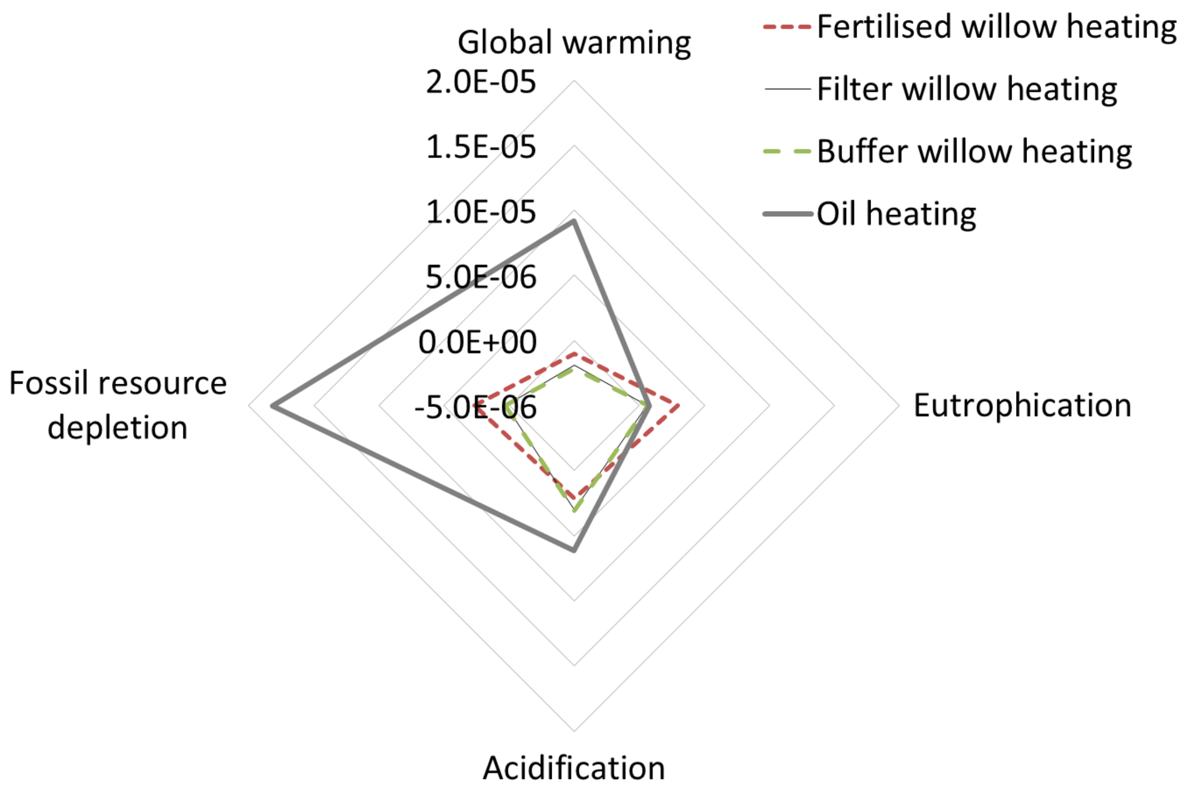

Figure 3. Normalised attributional LCA environmental burden scores for 1 MJ_{th} useful heat generated by willow wood chips sourced from Fertilised, Filter and Buffer willow plantations, compared with an oil heat reference system

After expanding ALCA boundaries to account for avoided oil heating, willow leads to significant reductions in GWP loading of between 9.5 Mg CO_2e ha^{-1} yr^{-1} for Buffer willow and 14.8 Mg CO_2e ha^{-1} yr^{-1} for Fertilised willow (Table 4), partly reflecting significant soil C sequestration (Figure 2). Eutrophication burdens for Fertilised willow are 7 kg PO_4e ha^{-1} yr^{-1}, owing to soil emissions (leaching) caused by application of fertilisers (Figure 2), compared with minor net reductions in eutrophication loadings for Buffer and Filter willow owing to avoided NO_x emissions from oil heat fuel chains.

Accounting for nutrient retention and applying a 0% ILUC factor in CLCA, Buffer and Filter willow achieve considerable reductions in eutrophication loadings, of 33.7 and 47.3 kg PO4e ha^{-1} yr^{-1}, respectively (Table 4). Reductions in GWP loadings are marginally lower owing to denitrification N_2O emissions. However, when 100% ILUC is considered in CLCA, Buffer and Filter willow lead to net increases in GWP loadings of 9.7 and 7.2 Mg CO_2e ha^{-1} yr^{-1}, respectively. Eutrophication burdens associated with ILUC offset approximately 20% of eutrophication savings through nutrient retention (Table 4). Acidification and resource depletion burdens and credits are unaffected by the CLCA methodology which assumes that the burden intensity of displaced production remains constant.

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Table 4: Net environmental burdens per hectare calculated using ALCA with an expanded boundary to consider oil heat replacement, and using CLCA with 0%, 50% and 100% indirect land use change (ILUC) factors

		ILUC		CO_2e	PO_4e	SO_2e	MJe
Fertilised willow	ALCA	NA	kg or MJ ha^{-1} yr^{-1}	-14,765	7.0	-12.2	-172,252
	CLCA	0%		-14,765	7.0	-12.2	-172,252
	CLCA	100%		4,348	14.5	-12.2	-172,252
Buffer willow	ALCA	NA	kg or MJ ha^{-1} yr^{-1}	-9,513	-0.5	-9.3	-102,799
	CLCA	0%		-9,441	-33.7	-9.3	-102,799
	CLCA	100%		9,673	-26.2	-9.3	-102,799
Filter willow	ALCA	NA	kg or MJ ha^{-1} yr^{-1}	-12,041	-0.6	-12.3	-133435
	CLCA	0%		-11,945	-47.3	-12.3	-133,435
	CLCA	100%		7,168	-39.8	-12.3	-133,435

<u>Skåne region consequential LCA results</u>

In the Water Purification scenario, environmental loadings to all four impact categories are reduced considerably if no ILUC is incurred (Table 5). Annual GWP loadings are reduced by 167,082 Mg CO_2e, EP loading by 626 Mg PO_4e and FRDP by 1,841 TJe. These figures represent relative changes in environmental loadings from arable production in Skåne of 15%, 5% and 27%, respectively (Table 5). Annual EP savings are dominated by avoided soil emissions (Figure 4), comprising annual reductions of 1,884 and 13 Mg, respectively, in N and P loading to water within Skåne. However, these reductions are somewhat offset by the EP burden associated with displaced production (Figure 4), which may be incurred in Skåne or further afield depending where compensatory production occurs (Figure 1). GHG emission savings are dominated by the substitution of oil heating (credit) and possible ILUC (burden) and are highly sensitive to the proportion of displaced food production that incurs ILUC (100% ILUC value displayed in Figure 4). Assuming all displaced food production drives ILUC at the global agricultural frontier, GHG emissions increase by 138,734 Mg yr^{-1} CO_2e, whilst applying a 50% ILUC factor leads to a net GHG emission saving of just 14,174 Mg yr^{-1} CO_2e (Table 5).

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Table 5. Changes in regional annual environmental loadings under the water purification and yield maximisation scenarios, calculated by consequential LCA applying 0%, 50% and 100% indirect land use change (ILUC) factors

		Mg CO_2e	Mg PO_4e	Mg SO_2e	GJe
0% ILUC	Water purification	-167,082	-626	-168	-1,840,851
		-15%	-5.3%	-2.8%	-27%
	Yield maximisation	-236,244	112	-195	-2,756,034
		-21%	0.9%	-3.2%	-40%
50% ILUC	Water purification	-14,174	-566	-168	-1,840,851
		-1%	-4.8%	-2.8%	-27%
	Yield maximisation	-83,336	172	-195	-2,756,034
		-7%	1.5%	-3.2%	-40%
100% ILUC	Water purification	138,734	-506	-168	-1,840,851
		12%	-4.3%	-2.8%	-27%
	Yield maximisation	69,572	232	-195	-2,756,034
		6%	2.0%	-3.2%	-40%

In the Yield Maximisation scenario, GWP, AP and FRDP savings are greater than in the Water Purification scenario (Table 5). Annual GHG emissions are reduced by 236,244 Mg CO_2e (21% of baseline emissions), whilst FRDP is reduced by 2,756 TJe (40% of baseline depletion). GHG emission savings are highly sensitive to ILUC factors in the Yield Maximisation scenario, though remain significant even when a 50% ILUC factor is applied (Table 5). However, in contrast to the Water Purification scenario, EP loading increases by 112 Mg PO_4e annually (1% of baseline eutrophication), and this doubles after applying a 100% ILUC factor.

Normalised consequential LCA results

Results Table 5 indicate the magnitude of environmental loading changes relative to baseline loadings from arable farming in Skåne, and are thus highly influenced by the magnitudes of baseline arable (agricultural activity) loadings. In Figure 5, annual loading changes for each scenario are normalised against total European environmental loadings (across all activities) for each impact category. Normalised results indicate that the eutrophication saving is of similar relative magnitude to the GHG emission saving at 0% ILUC, although still somewhat lower than the saving in resource depletion. Furthermore, the relative difference in performance of the two scenarios is greater for eutrophication than for global warming or resource depletion. Error bars representing uncertainty in yields and nutrient retention do not overlap for eutrophication loading changes in the Water Purification and Yield Maximisation scenarios, indicating that the eutrophication benefit of the Water Purification scenario is robust to these key uncertainties.

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DOI: 10.1007/s13280-016-0790-9

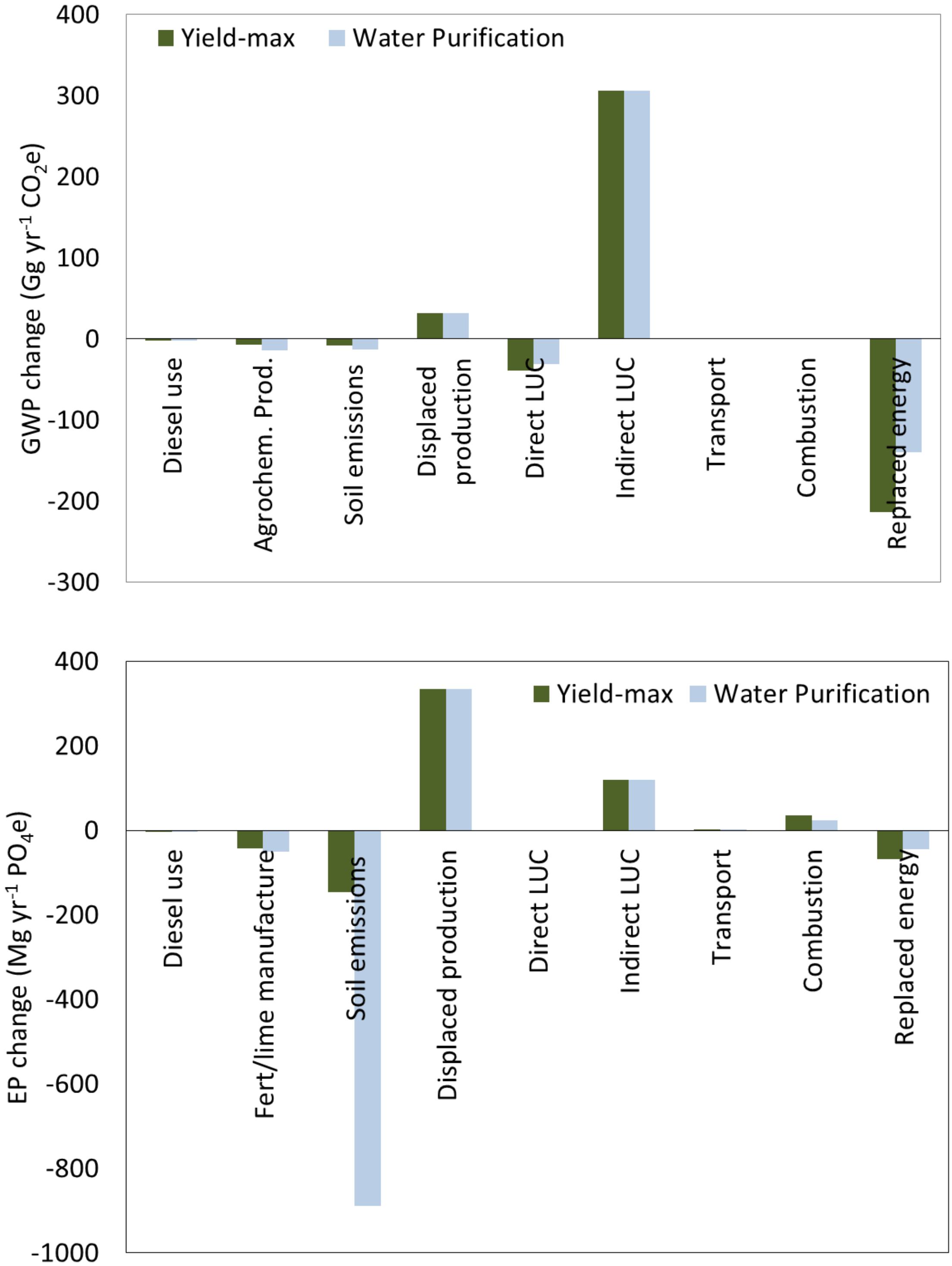

Figure 4. Processes contributing to environmental loading changes from the baseline situation for the Water Purification and Yield Maximisation scenarios, calculated by consequential LCA

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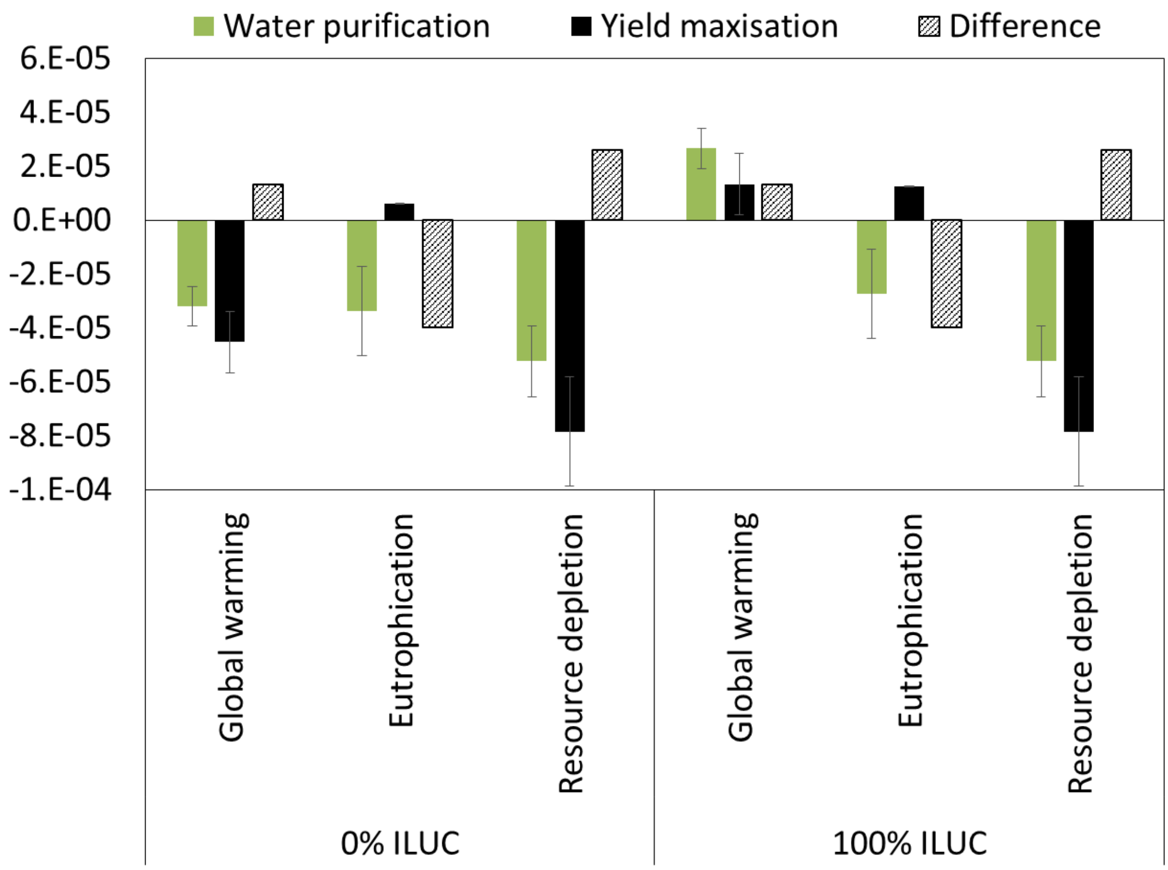

Figure 5. Environmental loading changes relative to the baseline situation for the Water purification and Yield maximisation scenarios normalised against European loadings, applying 0% (left) and 100% (right) indirect land use change factors. Error bars represent combined uncertainty in willow yield (±25%) and nutrient retention (±50%).

Discussion

Quantifying ecosystem service benefits

Consequential LCA provides a relevant framework to consider overall, direct and indirect, environmental effects of changes in land use, overcoming some of the constraints of attributional LCA. Plassmann (2012) highlighted the inverse relationship between soil C sequestration credits and productivity in product carbon footprints based on attributional LCA, which could encourage perverse conclusions on food and bioenergy production efficiency given the relative global scarcity of agricultural land and the large environmental consequences of agricultural expansion (e.g. Morton et al., 2006). Thus, consequential LCA provides a more comprehensive, if more uncertain, framework for evaluation of interventions involving land use change, as demonstrated by e.g. Tonini et al. (2012) and Styles et al. (2015a; 2016). However, up to now we are not aware of any studies that account for other ecosystem service benefits such as water purification within a consequential LCA framework. Water purification could also be accounted for within attributional LCA, but it would raise methodological questions about attribution of denitrification emissions and allocation of residual net burdens between energy and water purification “co-products”.

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DOI: 10.1007/s13280-016-0790-9

We demonstrate novel application of consequential LCA to quantify the environmental benefit of nutrient buffering delivered by bioenergy willow strategically planted within arable landscapes. Unfertilised willow cultivated on riparian buffer zones and tile drainage filtration areas can achieve greater net environmental benefit compared with randomly-sited fertilised willow cultivation, owing to a significant water purification effect that complements the climate regulation benefit associated with fossil fuel substitution. Ecosystem services such as water purification are highly dependent on site-specific hydrological connectivity and nutrient loading; one reason why increasing attention is being paid to the landscape context of bioenergy crop cultivation (Valentine et al., 2012; Bennett et al., 2014). Yet, such ecosystem services are rarely reflected in LCA studies that commonly rely on default emission factors independent of landscape context. The tools used within more holistic and spatially explicit ecosystem approaches are typically less quantitative than LCA, and neglect important indirect effects associated with displaced production that occur outside the geographic area of primary interest. Therefore, although challenging, time- and data-intensive, and more open to value-judgement than attributional LCA, integrating landscape-specific ecosystem service effects into consequential LCA could provide useful additional information to support sustainable land management and policy.

Limitations

The landscape scenarios studied here involved simplifications, such as that all nutrient applications to cropland were in the form of synthetic fertiliser rather than manures, and small areas of existing buffer strips on arable land in Skåne were ignored. Regional average fertiliser application rates may vary somewhat around the values reported by Jordbruksverket (2014b). Whilst these factors may affect the baseline environmental loadings and thus percentage loading changes in the scenarios, they do not have a significant influence on the absolute loading changes or normalised loading changes. Of greater importance is uncertainty over N and P retention rates of willow under different conditions. There is a need to investigate retention rates for willow, and alternative vegetation, planted on riparian buffer zones.

McKay (2011) noted that overall sediment losses are likely to be considerably lower for willow than for conventional arable agriculture, notwithstanding peak loss rates during harvesting and grub-up. Soil carbon sequestration and nutrient retention effects accounted for in this study may capture some of the environmental effects likely to be associated with sediment trapping, which could give rise to significant additional environmental credits for buffer willow cultivation. Whilst we assumed that willow was cultivated exclusively on mineral soils, significant GHG and eutrophication credits could be achieved via reduced mineralisation if willow replaces annual cultivation on peat soils, based on IPCC (2006) CO_2 and N_2O emission factors for peat soils under trees and annual cropping. Willow could also ameliorate stream peak flow and thus mitigate against flood risk. On the other hand, Berg (2002) highlight the value of open habitat corridors along streams, which can be detrimentally impacted by willow cultivation.

Ultimately, it is impossible to fully capture all ecosystem service effects in LCA, which will always involve simplifications, omissions and assumptions. Results presented here emphasise the value of capturing at least some major ecosystem service effects in LCA to inform sustainable land, climate and energy policy – so long as assumptions are transparently documented, and uncertainty and

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limitations acknowledged. As with all modelling approaches, the value of expanding LCA in this way will be to establish and contextualise cause-effect relationships that inform management and policy decisions, rather than to provide definitive numbers.

Water quality versus climate change

Unlike global warming burdens, eutrophication burdens attributable to willow cultivation are not offset by fossil fuel substitution (e.g. Tonini et al., 2012; Styles et al., 2015), leading to an important trade-off for fertilised willow cultivation in the form of higher overall eutrophication burdens. Strategic cultivation of unfertilised willow on buffer strips or filter zones avoids this trade-off, and in fact generates eutrophication credits, but at the expense of smaller savings in fossil fuel use and GHG emission compared with fertilised willow. Highly uncertain ILUC effects could negate GHG abatement by willow bioenergy, but results presented in this study were based on high rates of food production displacement to the global agricultural frontier – representing a worst case scenario. In the longer term, erosion protection and sheltering effects offered by trees could support adjacent arable cropping (Kort, 1988; Austin, 2014), mitigating food production displacement. Normalisation against European environmental loadings suggests that the relative eutrophication savings are greater than the relative GHG emission increases that could occur under worst case ILUC scenarios. Eutrophication is a major regional problem in Skåne and Baltic receiving waters, and the nitrogen cycle is the second most critically impacted planetary system according to Rockström et al. (2014), after biodiversity loss and ahead of climate change. Thus, eutrophication savings associated with strategically planted willow merit considerable attention (weighting) with respect to Skåne land use policy, and the eutrophication balance of bioenergy production more widely merits further scrutiny, alongside more extensively studied GHG balances.

Conclusion

Intensive arable agriculture is inherently leaky in terms of nutrient cycling (Pinder et al., 2012), and is often the dominant land use on fertile lowland plains where it is responsible for large eutrophication loadings to surface waters. Hitherto, consequential LCA studies of bioenergy systems have emphasised uncertain ILUC effects attributable to food production displacement, which Berndes et al. (2013) argue has distracted policy makers from genuine long-term GHG mitigation that can be achieved by bioenergy deployment. Our study highlights that, by also accounting for wider landscape-scale environmental effects within consequential LCA, a multi-dimensional case can be made for appropriately sited bioenergy production in the context of sustainable land management, environmental quality and renewable energy objectives. Specifically, our results indicate that willow cultivation on buffer and filter zones complements, rather than competes with, sustainable intensification of food production. It also represents a potentially profitable use of riparian buffer zones that may allow farmers to claim agri-environmental payments under the buffer scheme. Quantification of the water purification service delivered by strategically planted willow is an important step towards possible incentivisation, e.g. through payment for ecosystem service delivery.

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