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Research Paper

Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions

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ABSTRACT

A systematic review and meta-analysis were used to assess the current state of knowledge and quantify the effects of land use change (LUC) to second generation (2G), non-food bioenergy crops on soil organic carbon (SOC) and greenhouse gas (GHG) emissions of relevance to temperate zone agriculture. Following analysis from 138 original studies, transitions from arable to short rotation coppice (SRC, poplar or willow) or perennial grasses (mostly *Miscanthus* or switchgrass) resulted in increased SOC (+5.0 ± 7.8% and +25.7 ± 6.7% respectively). Transitions from grassland to SRC were broadly neutral (+3.7 ± 14.6%), whilst grassland to perennial grass transitions and forest to SRC both showed a decrease in SOC (−10.9 ± 4.3% and −11.4 ± 23.4% respectively). There were insufficient paired data to conduct a strict meta-analysis for GHG emissions but summary figures of general trends in GHGs from 188 original studies revealed increased and decreased soil CO_2 emissions following transition from forests and arable to perennial grasses. We demonstrate that significant knowledge gaps exist surrounding the effects of land use change to bioenergy on greenhouse gas balance, particularly for CH_4. There is also large uncertainty in quantifying transitions from grasslands and transitions to short rotation forestry. A striking finding of this review is the lack of empirical studies that are available to validate modelled data. Given that models are extensively use in the development of bioenergy LCA and sustainability criteria, this is an area where further long-term data sets are required.

1. Introduction

Over the last three hundred years, more than half of the global land surface has been impacted by human activity [1,2]. Land Use Change (LUC) is a major driver of global environmental change [3,4] and also an important driver of increased greenhouse gas (GHG) emissions, contributing to the 180 ± 80 Pg C rise in atmospheric CO_2 between 1750 and 2011 [5]. LUC may lead to altered soil organic carbon (SOC) and changes in a host of ecosystem services [6–10]. The majority of LUC is driven by demand for food, fibre and fuel and the nexus between water, energy and food is now clear, with much on-going debate amongst scientists and policy makers on how we can achieve intensification of land use whilst at the same time preserving natural capital [11].

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There is an urgent need to mitigate the impacts of LUC, through sustainable land management strategies that include renewable energy technologies such as bioenergy, which has the potential to provide both carbon sequestration and a displacement of fossil-based fuels. Renewable energy targets across Europe and in both national [12] and international [13] future energy scenarios, suggest a central role for bioenergy where 10–20% of primary energy supply is provided from green plants in some form, including to generate electricity, heat and liquid transport fuel [14]. In order to reach future targets, a substantial increase in bioenergy crop plantings will be required. In the UK, for example, recent estimates show that there is a potential 35 000 km^2 of land available for dedicated lignocellulosic bioenergy cropping that would not impact on the highest quality agricultural land [15], with the potential to supply 66% and 62% of the total heat and electricity demand, respectively [16]. It is therefore important to quantify the direct impacts of LUC for GHG balance, SOC and other landscape scale effects, so that appropriate land management strategies can be put in place.

The carbon and GHG balance associated with dedicated bioenergy crops has been the subject of considerable debate in recent years. Empirical measurements on the direct impacts of land use change to bioenergy are only just starting to emerge [e.g. [17, 18]], with the indirect impacts of land-use change remaining difficult to quantify [19–22]. There are also conflicting messages from a fragmented literature regarding LUC, as these effects can vary depending on the starting land use, the initial carbon stocks, the management regime and the climatic region where the land exists. Quantitative syntheses are lacking which are able to bring this body of research together in a succinct analysis. Meta-analysis provides a useful approach to identify the general trends in the effects of LUC to bioenergy cropping on GHG emissions and SOC. Meta-analyses are becoming increasingly common in the scientific literature, expanding out from the traditional subject area of clinical medicine into ecology and environmental science [23]. Meta-analyses are a robust statistical method of identifying trends and patterns that exist within the literature which may be overlooked or undervalued in a traditional narrative review [24]. Gou and Gifford [25] performed a highly-cited meta-analysis of the effect of LUC on SOC and found that transitions from forest or to arable resulted in decreased SOC, with several other large scale meta-analyses taking place in this research area following this [26–28]. Here we are able to complement these studies by focussing our investigation on the effects of land use change to bioenergy cropping in temperate zones, relevant to recent policy development including the Renewable Energy Directive (RED) which requires a better understanding of LUC to bioenergy cropping for GHG savings [29].

The aim of this study was to assess the state of the current literature on LUC effects to bioenergy and to quantify the scale of these effects specifically focusing on SOC and GHG emissions. Our 'controls' were existing land uses - arable, grassland and forests, and our 'treatments' were the bioenergy land uses - '1st generation' crop ('1G'; food crops, e.g. wheat, corn, sugar beet etc.) and '2nd generation' crops (2G) grouped into short rotation coppice 'SRC' (short rotation coppice willow or poplar), 'perennial grasses' (e.g. *Miscanthus*, switchgrass etc.) and short rotation forestry 'SRF' (e.g. poplar, alder, birch, beech etc.; Table 1). The outcomes from this study will assist decision making for both land managers and policy makers regarding the effects of LUC to bioenergy cropping in temperate regions. In addition, we identify existing knowledge gaps which may be present to help direct future research efforts to close such knowledge gaps.

2. Materials & methods

2.1. Systematic review scope

We followed standard systematic review methodologies [30] to collate empirical studies from temperate regions that measured SOC or GHGs in 'treatment' bioenergy plantations, relative to 'control' existing common land uses - arable, grassland and forests (see Appendix A for glossary). The land use transitions of interest were grouped to cover a conversion from arable, grassland or forest to 1G, SRC, perennial grasses or SRF (Table 1).

We used a structured search string to ensure all relevant literature was captured without bias (see Appendix B for systematic search query methodology). To ensure meaningful comparisons, publications had to satisfy strict inclusion criteria. These were as follows: (1) appropriate response metrics must be measured in the publications: SOC measures as C (carbon) in units of t ha^{-1} y^{-1} (or a convertible figure) and GHG emissions for crop life cycle, partitioned into CO_2, N_2O, CH_4 or 'all' measured as carbon dioxide equivalents (CO_2e) in units of t ha^{-1} y^{-1} (or convertible figures); (2) studies featured transitions of interest (Table 1); (3) studies had to report both pre-existing (control) and post-conversion land-use (treatment) values for the response metric(s) of interest. Studies were also eligible if they documented a land conversion not strictly for use as bioenergy, but used similar land management practices as would be used for bioenergy cultivation. (4) study locations were relevant to a temperate climate i.e. within the 23.5° and 66.5° latitudinal band and (5) the species were inclusive of 1G and 2G bioenergy crops (Table 1), but only those able to be cultivated in a temperate region.

Table 1 – Grouping of bioenergy land use types and potential crop species.

Bioenergy land use type	Inclusive species	
1st generation (1G)	Wheat	Triticale
	Oil Seed Rape	Canola
	Corn	Sugar Beet
	Barley	
Short rotation coppice (SRC)	Willow	
	Poplar	
Perennial grasses	Miscanthus	
	Switchgrass	
	Reed canary grass	
Short rotation forestry (SRF)	Eucalyptus	Conifer
	Alder	Beech
	Birch	Poplar
	Sycamore	

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Data from relevant publications were extracted in pre-defined units for the meta-analysis; standard unit conversions were performed where necessary. Authors were contacted in instances where data were insufficiently reported for inclusion in the meta-analysis. For those studies that reported data in figures only, numerical information was extracted using DATATHIEF [31].

2.2. Statistical analysis

2.2.1. Effect size calculation

Three key values are required to perform a meta-analysis, a mean ($\bar{x}$), a standard deviation (SD) and a sample size (n) for the control and treatment. For each comparison, the log response ratio (lnR) of SOC was calculated between a pre-existing land use (control group) and bioenergy (treatment group)

$$lnR = ln(\bar{x}_{bioenergy}) - ln(\bar{x}_{control}) \quad (2.1)$$

where $\bar{x}_{bioenergy}$ treatment is the mean SOC of bioenergy, post-conversion land use and $\bar{x}_{control}$ is the mean SOC of the control, pre-conversion land use. The lnR describes the proportional difference in the response metric between control and treatment groups. The natural log transformation of the response ratio both linearizes the metric, treating deviations in the denominator and the numerator as equal, and normalises its otherwise skewed distribution [32]. lnR values can be transformed to show change more intuitively as percentage difference from control groups.

A negative effect size (lnR) indicates loss in SOC as a result of LUC to bioenergy; a positive effect size indicates an increase in SOC as a result of LUC to bioenergy.

2.2.2. Meta-analysis

Random-effects models [33] were applied to calculate overall effect sizes for the following LUC for SOC: Arable to perennial grasses, arable to SRC, forest to SRC, grass to perennial grasses and grass to SRC. Studies included in this meta-analysis differ intrinsically in the methods used, site characteristics, sampling depth etc. Random-effects models allow for different study-specific effect sizes and assumes that heterogeneity among studies in their true effect sizes is due to random variation around the overall mean effect of the population of studies [33]. Each study included in the meta-analysis is assumed to be a random sample of a relevant distribution of effects, and the combined effect estimates the mean effect in this distribution. If the 95% confidence intervals did not overlap zero, the treatment bioenergy land use transition was regarded as having significantly different SOC content than the control land use. The meta-analysis was weighted in that each study-wise effect size was weighted by the inverse of its variance [24,32]. All models used the restricted maximum-likelihood estimation (REML) estimate. Grand log response ratios characterising the mean log response ratio for a population of studies were back-transformed to represent more intuitive changes in terms of percentage difference in SOC relative to controls. We examined heterogeneity, the between-study variation, using a heterogeneity measure (Q), calculated by weighting the sum of squared differences between individual effects and the pooled effect, tested against a chi-square distribution. Restricted maximum-likelihood estimation was used to estimate T^2 (see Appendix C for calculations [34]). All statistical analyses and calculations were performed in R version 3.0.2 [35] using the METAFOR package 1.9-3 [36].

Publication bias may be suspected if small positive studies are present without small negative studies [37]. This was tested by assessing funnel plots of effect size vs. standard error of the effect size (see Appendix D [38]) using the METAFOR package [36]. Weighted regression with multiplicative dispersion using standard error as the predictor did not detect funnel plot asymmetry, (t=-1.66. $_{df} = 136$, $p = 0.0994$), indicating no evidence of publication bias.

A meta-analysis on the effect of LUC to bioenergy on GHG emissions was not conducted due to insufficient reporting of error terms. Therefore, with the data that were available, an arithmetic mean of the studies were calculated and presented in a standard histogram.

3. Results

Contrary to traditional statistical tests, in the case of a meta-analysis, the magnitude of the effect size is more important for interpretation of the results than the p-value [33]. p-values are able to indicate, with 95% confidence, that the result differs to the null hypothesis, and when read are rarely considered with the sample size. Effects sizes, produced as a result of meta-analysis, take into account the sample size of the included studies and weight them accordingly, thereby relieving the study of any bias due to larger sample sizes. Therefore whilst a grand mean may not be statistically significant it should not be discounted as not being of relevance to the research question; as the magnitude of the effect size indicates the general trends of the effects of LUC on SOC as observed in the literature. The Q statistic, indicated that all transitions studied showed a significant degree of between-study heterogeneity.

The literature search yielded c.8000 publications. Of these, 27 satisfied inclusion criteria concerning climate, LUC, bioenergy crops and appropriate SOC and GHG data (Fig. 1). For SOC there were 13 publications amounting to a total of 138 observations. There were insufficient data to conduct a meta-analysis on GHG data; therefore a summary table of the available data was produced representing 14 publications containing 188 observations. Of all the land use transitions initially targeted, it was only possible to perform meta-analysis on 5 transitions for SOC, and 8 transitions contributed to a summary figure for GHG emissions (Table 2) of the total 12 possible transitions we aimed to cover.

Although SOC and GHG emissions are likely to vary with time since LUC and sampling depth, it was not possible to partition the studies according to these variables. The average time since transition across all studies was 5.5 years ($X_{max} = 16$, $X_{min} = 1$) for SOC. It was also not possible to partition by soil sampling depth, since the majority of studies considered SOC at the 0–30 cm profile only, although further depths were covered (ranges of 0–150 cm), these were inadequate for meta-analysis. Conclusions drawn from this meta-

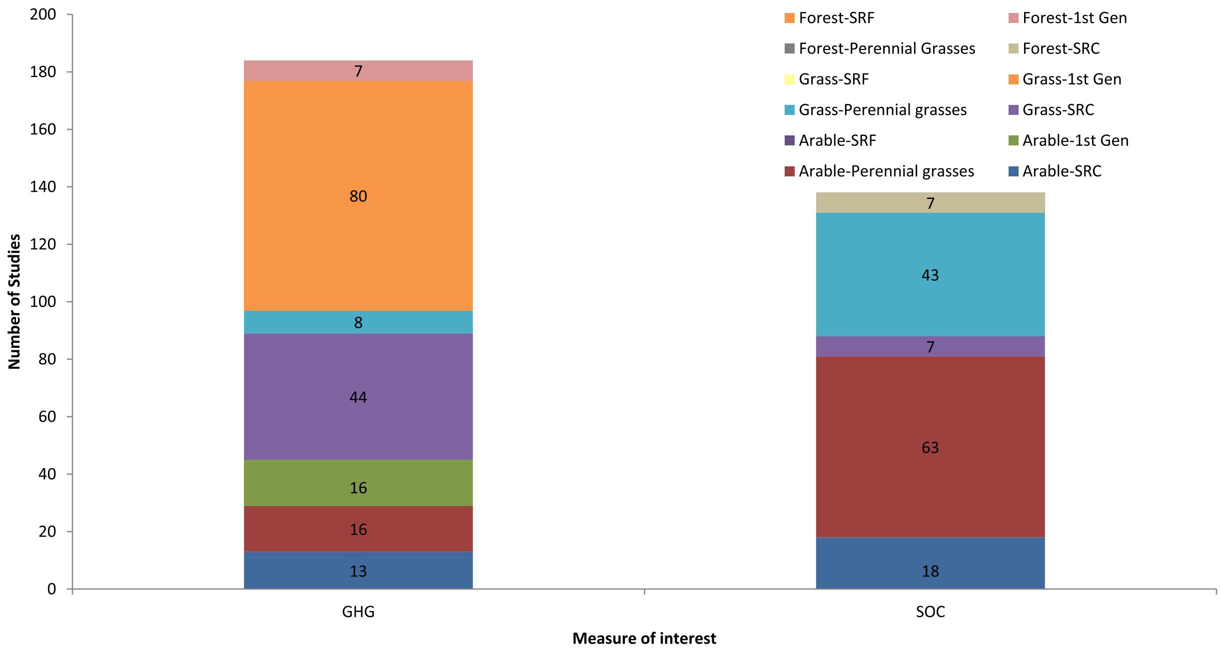

Fig. 1 – Total number of studies which contributed to each analysis for all combined greenhouse gases (GHG) and soil organic carbon (SOC).

analysis can therefore be considered appropriate for the 0–30 cm sampling depth and c.6 years after transition to bioenergy cropping (Table 3). Longer-term experimental studies are lacking beyond this time-frame.

3.1. *Soil organic carbon*

Sufficient data were available to analyse the effects of LUC on SOC from arable to both perennial grasses and SRC, both showing that a transition to 2G cropping resulted in an increase in SOC (Table 4, Figs. 2 and 3). Arable to perennial grasses showed a significant increase in SOC of +25% (±6.7%). Arable to SRC showed an increase in SOC of +5.0% (±7.8%), though this was not significant. As for forest transitions, there were only sufficient data for a transition to SRC, showing a loss in SOC of −11.4% (±23.4%), though this was not significant. There was not a consensus on the effect of LUC to bioenergy cropping on SOC for grassland transitions. A transition from grass to perennial grass showing a significant decrease in SOC of −10.9% (±4.3%) whilst a transition to SRC showed a slight increase in SOC of +3.7% (±14.6%), though this was not significant.

3.2. *Greenhouse gas emissions*

Meta-analysis of GHG emissions between control and treatment land uses was not possible due to inadequate reporting standards concerning error terms. Sufficient data were available to assess the effects on all GHGs of interest but not all transitions were covered. Figs. 4–6 show the general trends of GHG changes as a result of LUC to bioenergy crops in the form of a summary histogram. The effect of LUC to bioenergy on CO_2 emissions can be seen in Fig. 4, showing that transitions from arable to 2G crops results in reduced emissions of CO_2, -2.1 and −2.2 t ha^{-1} y^{-1} for SRC and perennial grasses respectively. The transition from arable to 1G cropping was broadly neutral with the few differences likely to be due to management regime, rather than crop species planted. Grassland to perennial grasses showed a slight reduction in CO_2 emissions of −0.8 t ha^{-1} y^{-1} and grass to 1G showed a slight increase in CO_2 emissions of 1.9 t ha^{-1} y^{-1}. Grassland to SRC showed a more pronounced increase in CO_2 emissions of 6.7 t ha^{-1} y^{-1}, though this transition represents a change after only 7 years, whereas the previous grass transitions were around 25 year post-transition (Table 5). Forest transitions to bioenergy show the most pronounced changes in CO_2 emissions, with a transition to perennial grasses resulting in an increase of 20.8 t ha^{-1} y^{-1} and a transition to 1G cropping showing the most pronounced emissions at 26.5 t ha^{-1} y^{-1}.

Fig. 5 shows the effect of LUC to bioenergy on N_2O emissions for 5 transitions; there were insufficient data for the other land use transitions, as indicated on the graph. Similarly the effect of conversion from arable to 2G bioenergy cropping was a very small reduction of −0.2 t ha^{-1} y^{-1} for both SRC and perennial grasses for N_2O. There was little effect on the conversion from arable to 1G cropping of −0.1 t ha^{-1} y^{-1} which again may be due to a change in management regime. The only transition where there was sufficient data for LUC from grassland to 2G cropping was grass to SRC which showed a slight increase in N_2O emissions (2.5 t ha^{-1} y^{-1}), a transition to 1G showed an emission of 0.5 t ha^{-1} y^{-1}.

There were very limited data to assess the effects of LUC to bioenergy on methane emissions, with only 3 transitions being covered (Fig. 6). All transitions showed a very slight

Table 2 – Summary of data sufficiency for meta-analysis for land-use change to bioenergy cropping systems. Ticks indicate where there were sufficient data for meta-analyses and crosses indicate where there were insufficient data for meta-analyses. Where meta-analyses were not possible a summary figure was constructed.

	Soil organic carbon	GHG emissions
Arable → SRC	✓	Summary figure
Grass → SRC	✓	Summary figure
Forest → SRC	✓	✗
Arable→ Perennial Grasses	✓	Summary figure
Grass → Perennial Grasses	✓	Summary figure
Forest → Perennial Grasses	✗	Summary figure
Arable → 1st Gen Crops	✗	Summary figure
Grass → 1st Gen Crops	✗	Summary figure
Forest → 1st Gen Crops	✗	Summary figure
Arable → SRF	✗	✗
Grass → SRF	✗	✗
Forest → SRF	✗	✗

reduction in CH_4 emissions; arable to perennial grasses and SRC with −0.4 and −0.2 t ha^{-1} y^{-1} respectively, and grass to SRC with −0.007 t ha^{-1} y^{-1}. Current literature [17,18,64,65] and work currently being undertaken in the UK [66] indicates that methane only plays a minor role in the overall GHG balance during LUC to bioenergy cropping systems.

4. Discussion

4.1. *Main outcomes*

Using a total of 13 publications, containing 138 studies we have quantified the effects of LUC to bioenergy cropping for 5 out of 12 possible transitions for SOC. There were insufficient data to conduct a strict meta-analysis on GHG data, so a summary figure was constructed using 14 publications containing 188 studies for CO_2, covering 8 of the 12 LUC transitions, N_2O and CH_4, covering 5 and 3 of the 12 transitions, respectively. The transitions investigated in this work are appropriate for the land use types currently under cultivation across Europe and the USA. It is unlikely that we will see land converted from forest or agricultural croplands to bioenergy cropping, in these areas, with the most likely transitions from grasslands, ex-set aside lands or degraded lands that are unsuitable for crop production. This is concerning since most studies consider conversions from croplands and forests, in the case of transitions related to tropical ecosystems [27] where conversion from primary forests to sugarcane and maize resulted in more than a 25% loss of SOC. Here we have focused entirely on temperate zone LUC and provided a firm evidence base for policy and land management strategies.

For GHG emissions the effect of a conversion to bioenergy copping is usually seen immediately, with land preparation and planting resulting in increased emissions [67]. After establishment, the crop may enable a net gain in SOC, until the net sequestration by the crop is equal to that of the initial emission event. It is only past this point, when the ‘carbon debt’ has been paid, that the crop be considered to be actively adding to the carbon sink. A number of LCA studies overlook the importance of the establishment phase of bioenergy planting following land conversions, as these will have a large influence over the resulting carbon debt which has to be repaid and similarly do not take management events into account, such as harvesting and fertilisation [68]. Several studies have shown that the initial landscape conditions and land-use history are key to determining the time required to repay the carbon debt as a result of LUC to bioenergy cropping systems [69]. Arable to bioenergy cropping showed decreases in emissions of CO_2, N_2O and CH_4 in this analysis, across a timeframe of 1.5–23 years. Though the difference between 1.5 years and 23 years post-conversion is rather large the general trend is a decrease in emissions, with the mean time since transition approximately 10 years (Table 5). This change may reflect a difference in structure of the species, with 2G crops accumulating more biomass with a deeper rooting system [70] and as the result of change in management practice with reduced inputs such as fertiliser. Recent work on SRC and *Miscanthus* suggests that nitrogen fertiliser application may be the most significant management practice determining GHG balance [68,71].

For soil carbon a much longer time frame is often required to restore the land to its original, or new equilibrium, carbon stock as this pool develops much slower over time compared to the rate of GHG emissions [72]. The amount of carbon present in soil depends on the rate of decomposition of SOC to CO_2 by micro-organisms and the rate of organic matter input from plant residues; in temperate climates a new equilibrium is often achieved with an exponential change time constant of 30–40 years [73]. Soil carbon assimilation rates will vary from site to site and depend on the existing carbon pool, the soil properties and climatic region [61,74]. It is estimated that a conversion from annual to perennial rotations, or vice versa, will influence the SOC in mineral soils over a period of 30–50 years in temperate regions [75]. In our study we found that a conversion from arable to perennial grasses and SRC resulted in a net increase in the SOC of 25.7%

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Table 3 – Summary of changes in SOC as a result of LUC to bioenergy, showing time since transition and soil depth of included studies.

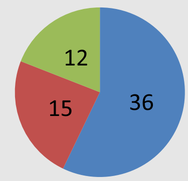
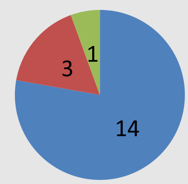
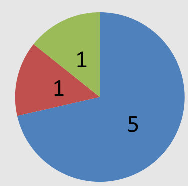
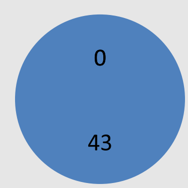
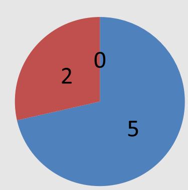
Transition	Change in SOC	Average time since transition (years)			Average soil depth (number of studies at each depth)
	(% ± SE)	Mean	X_{min}	X_{max}	0-30cm / 30-60cm / 60cm+
Arable – Perennial Grasses	25.7 ± 6.7	5.4	2	16	
Arable – SRC	5.0 ± 7.8	5.7	1	9	
Forest – SRC	−11.4 ± 23.4	5.7	2	9	
Grass – Perennial Grasses	−10.9 ± 4.3	5.8	3	6	
Grass - SRC	3.7 ± 14.6	7.1	2	15	

Table 4 – Meta-analysis outputs for land use transitions to bioenergy on Soil Organic Carbon (SOC). Negative % change denotes a loss in SOC. *n* = number of studies.

	ln(R)		% change		*p* value	*n*	Refs
	Effect size	SE	Percentage change	SE			
Arable – Perennial Grasses	0.23	0.03	25.7	6.7	<0.0001	63	[39–42,48,50,51]
Arable – SRC	0.05	0.04	5.0	7.8	0.2003	18	[41,43–47]
Forest – SRC	−0.1209	0.11	−11.4	23.4	0.2589	7	[43,46]
Grass – Perennial Grasses	−0.1158	0.0217	−10.9	4.3	<0.0001	43	[42,49]
Grass – SRC	0.04	0.07	3.7	14.6	0.6003	7	[46,47]

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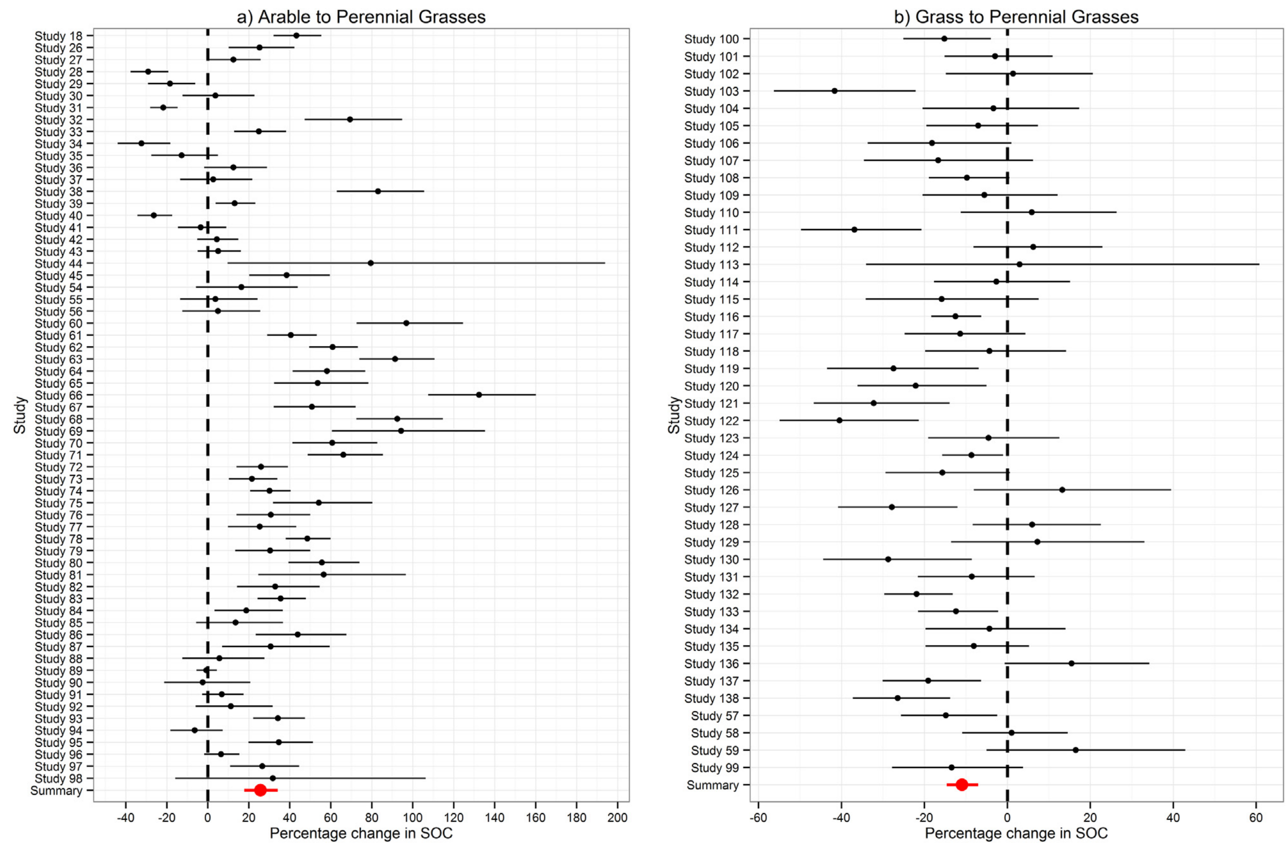

Fig. 2 – Percentage change of SOC as a result of land-use change to bioenergy crops, a) arable to perennial grass and b) grass to perennial grasses. Individual study data are shown and summary effect sizes are shown in red with the mean and 95% confidence intervals.

and 5.0% respectively. Higher carbon accumulation rates are observed in perennial crops than annual crops across the literature [74], with the management and inputs largely influencing this difference [72,76]. The limited data on forest conversions indicate that a LUC from forest to SRC resulted in an 11.4% decrease in SOC, but in the UK this would not be a likely transition given policy initiatives to increase forest cover. Whilst we observed that a transition from arable to 1G cropping was broadly neutral for GHG emissions, there is likely more research needed here. This LUC represents a change from a ‘food use’ of the land - in all cases wheat cultivation, transitioning to sugar and oil crops for biofuel production which tend to have higher associated GHG emissions and are more intensively managed [54]. In this type of analysis it is very difficult tease out the effects of management on SOC and emissions when considering arable or 1G, although several meta-analyses have completed in an attempt to elucidate these effects [27].

This analysis delivers a mixed message on the overall effect of converting grassland to 2G bioenergy cropping, with no definitive change being indicated. SOC was found to decline by 10.9% for grass to perennial grass and increase by 3.7% for grass to SRC. This difference may be explained by soil sampling depth, where transition to perennial grasses only considered in the top 30 cm of the soil and transition to SRC had some studies which considered the 30–60 cm profile. For GHG emissions there were also mixed messages as a result of LUC. For CO_2 there was a small decrease of 0.8 t ha^{-1} y^{-1} emissions, for a conversion from grass to perennial grasses and a conversion to SRC or 1st generation bioenergy cropping showed increased emissions for CO_2 and N_2O. This result was not entirely surprising given that grassland are known to be highly variable in both quality and soil carbon stocks [77]. There are also very large differences in how grasslands are managed which will have a large impact on both SOC and GHG emissions [78].

Results from previous meta-analyses may allow us to infer the effect of transitions which we were unable to capture in these analyses. Gou and Gifford [25] measured ‘plantations’ which are managed forests which may result in similar effects of planting to SRF and found that LUC from pasture and forest to planation resulted in a decreased in SOC of −10% and −13%, whereas a transition from arable cropping to forest plantation resulted in an 18% increase in SOC. Lagnière *et al.* [26] showed that the positive effects of afforestation on arable land on SOC was more pronounced than that in pastures and grasslands, which is in agreement with our findings where the most pronounced effects are as a result of LUC to 2G cropping whereas transitions from grassland to 2G show both increases and decreased in SOC.

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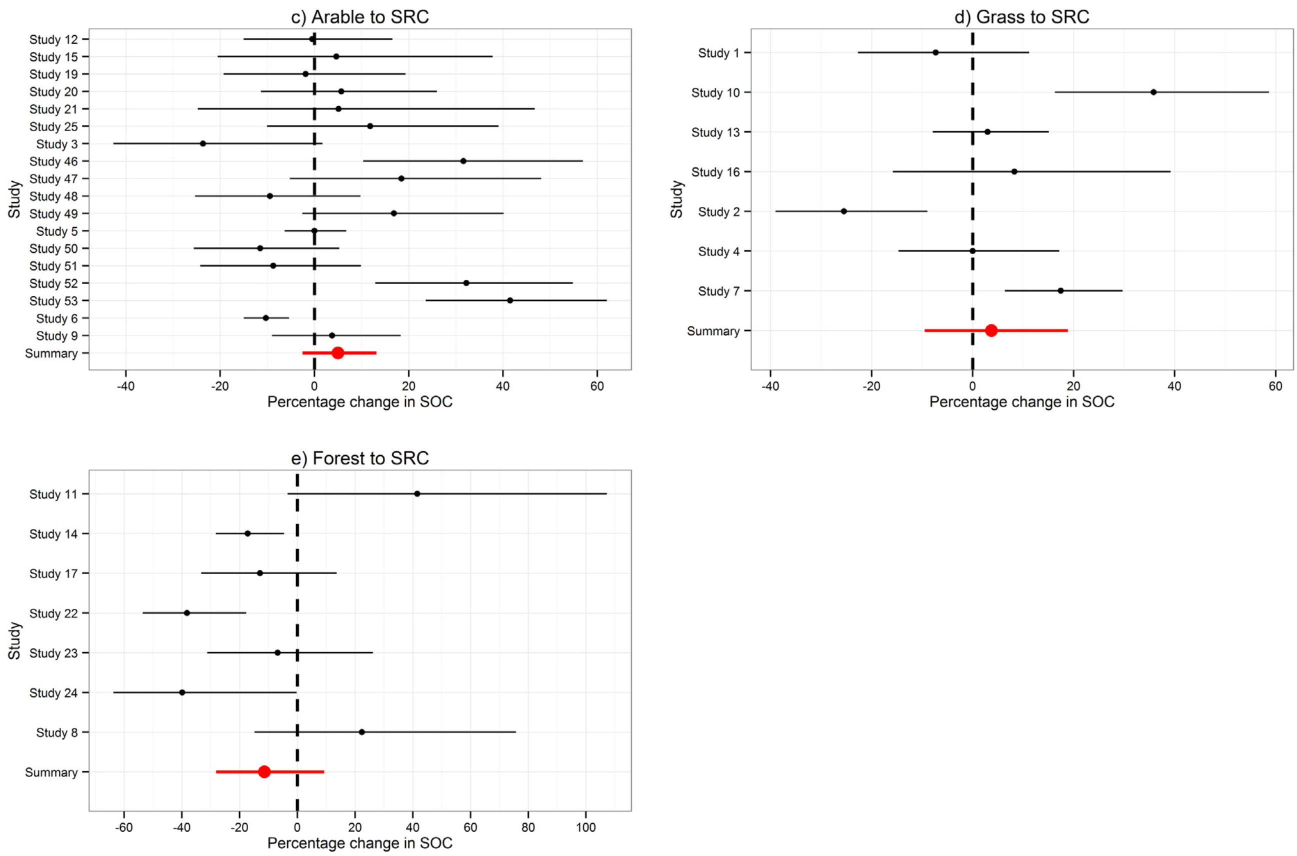
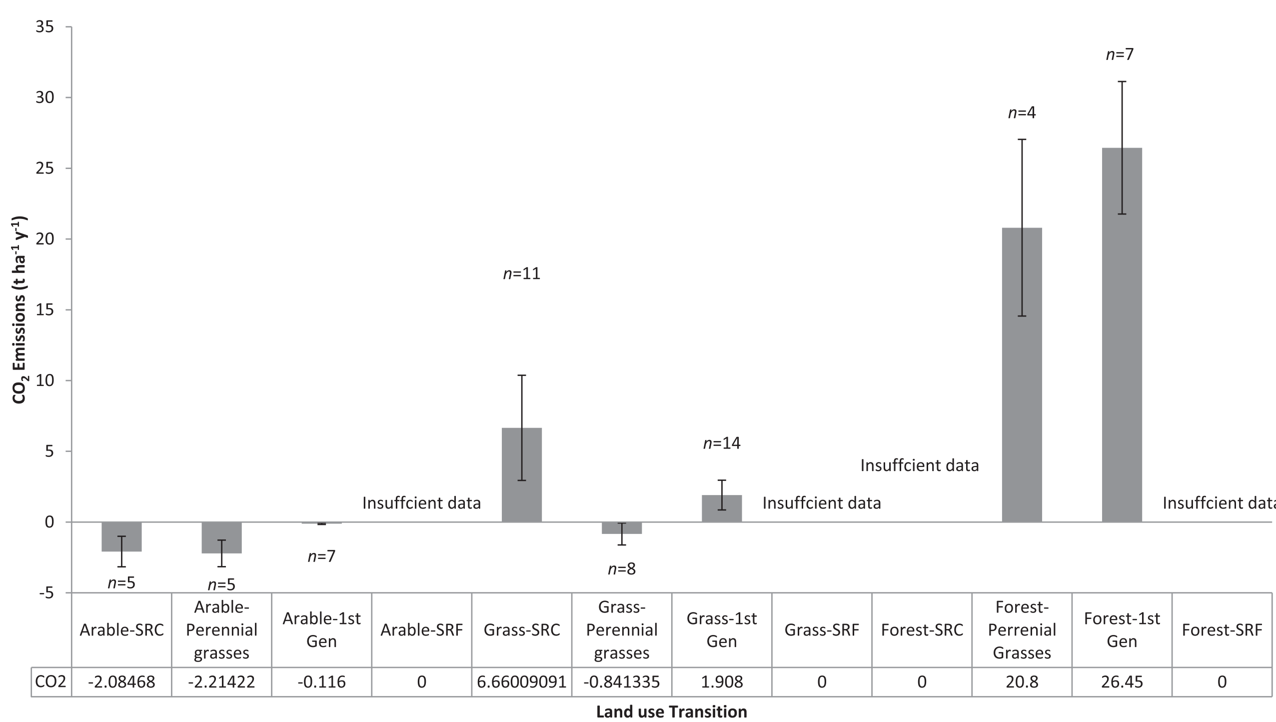


Fig. 3 – Percentage change of SOC as a result of land-use change to bioenergy crops, c) arable to SRC, d) grass to SRC and e) forest to SRC. Individual study data are shown and summary effect sizes are shown in red with the mean and 95% confidence intervals.



	Arable-SRC	Arable-Perennial grasses	Arable-1st Gen	Arable-SRF	Grass-SRC	Grass-Perennial grasses	Grass-1st Gen	Grass-SRF	Forest-SRC	Forest-Perennial Grasses	Forest-1st Gen	Forest-SRF
CO2	-2.08468	-2.21422	-0.116	0	6.66009091	-0.841335	1.908	0	0	20.8	26.45	0

Fig. 4 – The effect of land-use change to bioenergy on CO_2 emissions. Standard errors are shown with *n* denoting the number of observations. Positive values represent emissions and negative values represent sequestration. Refs: [18,41,53,54,57,59–63].

Table 5 – Summary of change GHG emissions as a result of LUC to bioenergy and the time since transition.

Transition		Change in GHG emissions as CO_2-eq ($t\ ha^{-1}\ y^{-1}$)	Average time since transition (years)
Arable – Perennial Grasses	CO_2	−2.2	14.8
	N_2O	−0.2	12.7
	CH_4	−0.4	9
Arable – SRC	CO_2	−2.1	12.5
	N_2O	−0.2	11.9
	CH_4	−0.2	6.5
Arable – 1st Gen	CO_2	−0.1	20
	N_2O	−0.1	20
Grass – Perennial Grasses	CO_2	−0.8	26.5
Grass – SRC	CO_2	6.7	7.1
	N_2O	2.5	2.2
	CH_4	−0.007	1.5
Grass – 1st Gen	CO_2	1.9	24.6
	N_2O	0.5	20
Forest – Perennial Grasses	CO_2	20.8	30
Forest – 1st Gen	CO_2	26.45	30

4.2. *Limitations*

The main limitation of this review was that a meta-analysis could not be conducted for GHG emissions because the available data were largely unsuitable for meta-analysis techniques. Studies that measure whole ecosystem GHG emissions, such as eddy covariance, require expensive equipment resulting in low replication, in many cases yielding an $n = 1$. There is also the need for the pre-existing land use to allow comparison of a transition. Many studies measure the carbon and GHG balance of individual fields, forests and arable land and several look at bioenergy cropping, however few look at them together where they are comparable. Even fewer studies have measured the existing land use and capture the conversion process to the new bioenergy plantation.

The data included in the analysis were annualised to allow comparisons across different studies. Since the largest impact of LUC may occur over the first few years post conversion [64,65,68], conversions studied over a shorter time frame are likely to show exaggerated changes in SOC and GHG emissions compared to those over a longer time-course and may be a source of error in the work reported here. However, an advantage of the studies included in this analysis is that they were all over similar time scales, up to approximately 15 years which for land use and SOC is relatively short term. However, the median time since LUC was only 3 years, and our analysis was limited by available data, which in future could be improved as new longer-term studies emerge. This highlights the importance of taking into account the amount of time needed, post-conversion, to determine the overall effect on the ecosystem, and if a loss of carbon is seen how long is will then be to repay this carbon debt. It should be noted that RCUK grants are rarely long enough for such experiments where at least 6–10 years data are needed.

4.3. *Knowledge gaps & future research*

This review has revealed a knowledge gap concerning the existence of robust, empirical studies investigating both the short-term and long-term consequences of LUC to bioenergy on SOC and GHG emissions in temperate regions. Just 13

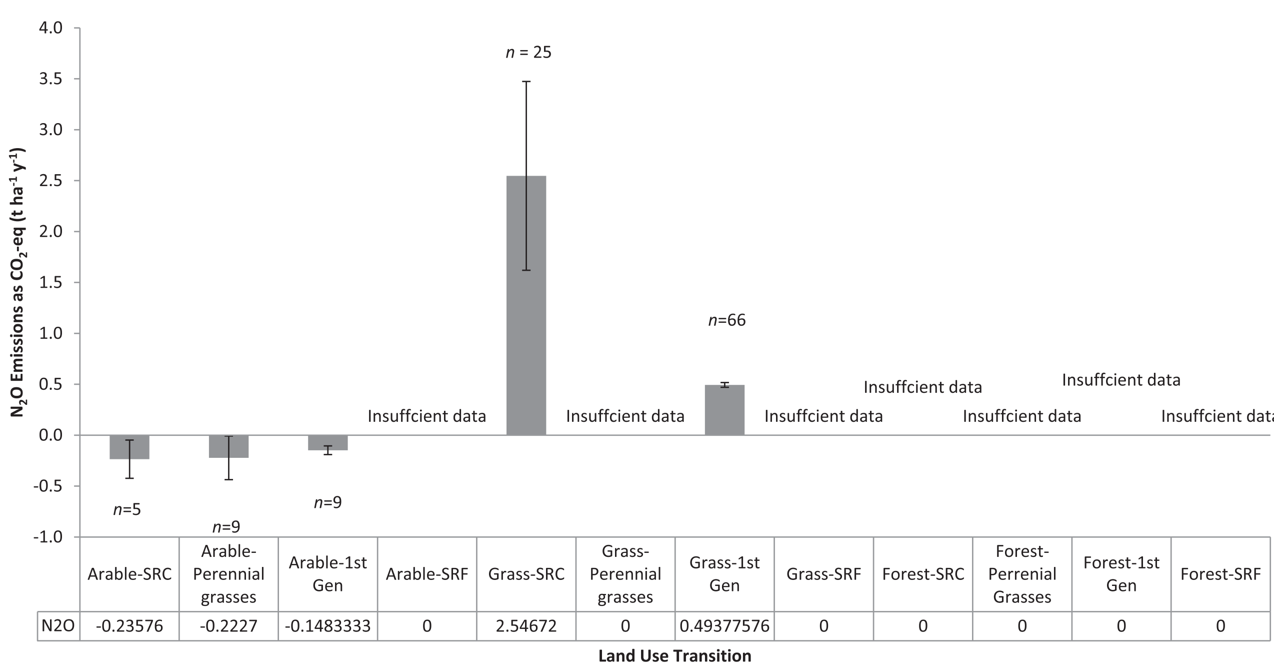


Fig. 5 – The effect of land-use change to bioenergy on N_2O emissions. Standard errors are shown with *n* denoting the number of observations. Positive values represent emissions and negative values represent sequestration. Refs: [18,41,52,54–56,58].

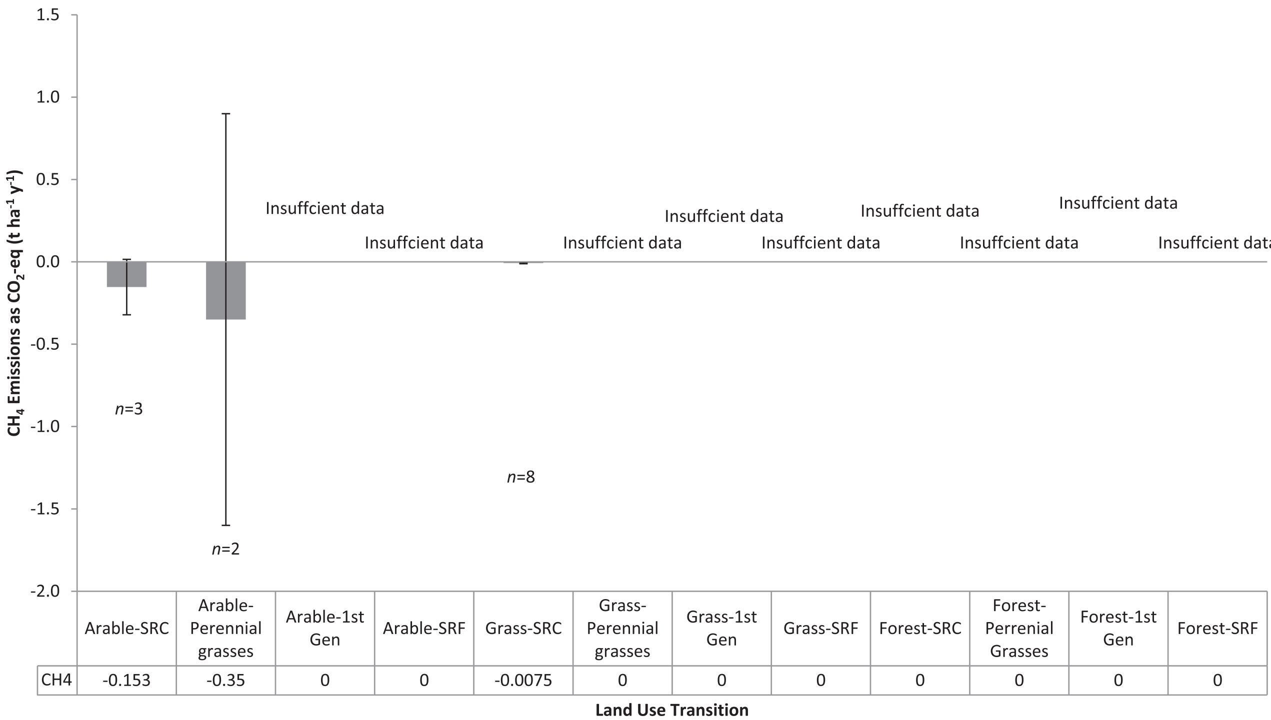


Fig. 6 – The effect of land-use change to bioenergy on CH_4 emissions. Standard errors are shown with *n* denoting the number of observations. Positive values represent emissions and negative values represent sequestration. Refs: [18,41,59].

and 14 published studies were available for meta-analysis for SOC and GHG emissions, respectively. A reason for this small number is that many studies incorporated experimental designs that suffered from pseudoreplication [79]. Furthermore, several studies had investigated SOC and GHG emissions in response to the LUC, but did not report the summary statistics that are required for meta-analysis ($\bar{x}$, *n* and SE). We urge that studies on LUC to bioenergy report such statistics to allow their inclusion in future meta-analyses. We assert the framework proposed by Whitlock [80] which states data should be archived with enough clarity and supporting information that they can be accurately interpreted by others.

Whilst research in this area is increasing, the most valuable data sets will come in two forms (1) replicated long term monitoring of an existing land use measuring the change of interest, monitoring of a the conversion process and monitoring of the bioenergy crop and (2) a paired-site approach measuring two sites in parallel, with one representing an initial land use and the other representing the post-conversion bioenergy crop. The ideal design for assessing the impacts of LUC to bioenergy would be in the form of a *Before-After, Control-Impact* (BACI) design as this allows for both a change in the land use but the maintenance of a control site to allow any climatic variability to be taken into account [81]. Whilst these study designs are most desirable they are extremely difficult to execute on field scale due to the space and funds required, especially to measure whole ecosystem GHG balance.

For the transitions covered here there are two that demand further consideration. Firstly, transitions from grassland and secondly the lack of publications on transitions to SRF. There is large uncertainty surrounding transitions from grassland, a potentially very large carbon sink [82] with a global land converge of 25% of the earth's land surface [83]. Grassland degradation is a large threat to these sinks as recent results show globally almost 50% grassland have been degraded, with climate change and human activities being the dominant causes resulting in 45.5% and 32.5% degradation respectively [84]. Grasslands have been shown to be extremely variable in their carbon stocks across different climatic gradients and management regimes [77] with sampling depth and bulk density considerations varying across published studies. In particular the effect of management of these grassland, including fertiliser application, type and intensity of grazing and rotation length, greatly affecting the overall GHG balance, especially with regard to N_2O and CH_4 emissions which are more radiatively active than CO_2 [85]. Understanding these effects and applying the appropriate land management strategy, such as planting system and grazing intensity can help to manage the land more effectively for carbon sequestration [86]. As the average rotation of SRF is 18–20 years, it is difficult to cover the whole rotation period, with many studies thus far reporting mainly on biomass yields and effects of management regimes [87]. It is likely that transitions to SRF, from arable and (with less certainty) grassland will result in net GHG savings and increase SOC [88–91].

Based on the limitations and knowledge gaps discussed above we recommend [66,92]:

1. Studies should be designed to monitor the entire transition since capturing the effects of the conversion process would enhance our understanding of LUC to bioenergy.

2. Monitoring experiments at commercial scale should be maintained to assess the long-term effects of LUC.
3. Increased empirical research on the effects of LUC, especially for grassland transitions including rotational and permanent grass, and for SRF where there are limited data.
4. Authors are urged to make all data freely available with appropriate error terms, for meta-analysis.

In summary, we have quantified the impacts of LUC to bioenergy cropping on SOC and GHG balance. This has identified LUC from arable, in general to lead to increased SOC, with LUC from forests to be associated with reduced SOC and enhanced GHG emissions. Grasslands are highly variable and uncertain in their response to LUC to bioenergy and given their widespread occurrence across the temperate landscape, they remain a cause for concern and one of the main areas where future research efforts should be focussed.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.biombioe.2015.05.008.

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