Applied Energy 179 (2016) 847–863

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Improving bioenergy sustainability evaluations by using soil nitrogen balance coupled with life cycle assessment: A case study for electricity generated from rye biomass

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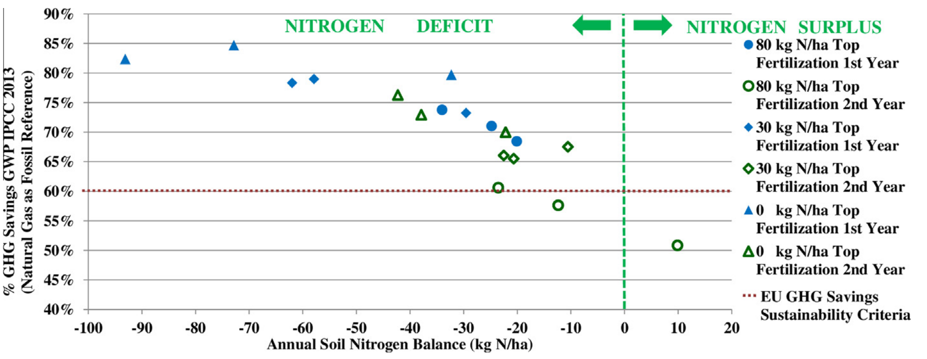
HIGHLIGHTS

- We assess the environmental sustainability of electricity production of rye biomass.
- We establish trials to compare the effects of three nitrogen fertilization doses.
- We combined life cycle assessment with soil nitrogen balance.
- Rye trials with higher GHG savings produce greater soil nitrogen deficits.
- The usefulness of soil nitrogen balance coupled with life cycle assessment is probed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 31 December 2015
Received in revised form 5 July 2016
Accepted 9 July 2016

Keywords:
Bioenergy
Sustainability
Life cycle assessment (LCA)
Soil nitrogen balance
Fertilizers
Energy crops

ABSTRACT

The use of Life Cycle Assessment (LCA) as an environmental tool to evaluate the sustainability of different bioenergy pathways has become a common practice since the European Renewable Energy Directive was published in 2009. In the evaluation of bioenergy produced out from dedicated energy crops, nitrogen fertilizer production and use are commonly identified as the most important contributors to fossil energy consumption and to several environmental impacts categories including Global Warming Potential. In considering the impacts produced by the nitrogen fertilization of energy crops and in addition to the effects of fertilization schemes on the biomass yield, more attention should be paid to the changes in soil nitrogen to know if fertilization doses and application schemes are sufficient enough to maintain soil nitrogen stocks and ensure that soil quality is preserved for future years. To this aim, in this work soil nitrogen balance is used as an indicator to estimate the evolution of soil nitrogen stocks and complement LCA calculations. In this paper, the effects of three nitrogen top fertilization doses (null, 30 and 80 kg N/(ha y)) used for rye cultivation are compared when ry is grown as a dedicated energy crop for electricity generation under the Spanish province of Soria conditions. A LCA was carried out using experimental crop testing results and a centralised (25 MWe) straw power plant data in combination with soil nitrogen balance obtained in each of the experimental crop trials. After that, the LCA results were compared with those obtained when electricity is generated from natural gas in Spanish power plants. According to the average calculations, each additional kg N/(ha y) applied in top fertilization produces a reduction of 0.18% on GHG savings with respect to natural gas electricity, as well as a worsening in the energy balance of 0.00084 TJ fossil energy per TJ of electricity generated but reduces soil nitrogen deficit in

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http://dx.doi.org/10.1016/j.apenergy.2016.07.022

Nomenclature

Variables

Symbols	Description (Units)
E	electrical energy generated (MJe/(ha y))
RY	rye whole plant yield at 0% humidity (kg crop/(ha y))
H	humidity percentage of the biomass (kg water/kg crop)
SL	bales storage loses (dimensionless)
$NHV_{CP,H}$	net heating value of rye at constant pressure and at H% humidity (MJ/kg)
η	conversion efficiency of the biomass power plant (MJe/MJ crop)
$NHV_{CP,0}$	net heating value of rye at constant pressure and at 0% humidity (MJ/kg)
AM	amount of machinery (kg/(ha y))
W	weight of the machinery (kg)
OR	operating rate (h/(ha y))
LT	lifetime of the machinery (h)
N_2O	emissions of N_2O to the air (kg N_2O/(ha y))
N_{tot}	total nitrogen input from fertilizers (kg N/(ha y))
N_{cr}	nitrogen contained in crop residues (kg N/(ha y))
N_NH_3	losses of N in form of NH_3 (kg N-NH_3/(ha y))
$N\_NO_3^-$	losses of N in form of NO_3^- (kg N-NO_3^-/(ha y))
P	precipitation plus irrigation if it exits (mm/y)
c	clay percentage of the soil (%)
L	root depth of the crop (m)
S	total nitrogen supply (kg N/(ha y))
N_{org}	nitrogen content of soil organic matter (kg N/ha)
U	nitrogen uptake by the crop (kg N/(ha y))
N_Er	nitrogen losses by soil erosion that reach surface water (kg N/(ha y))
S_{er}	quantity of soil eroded (kg soil/(ha y))
N_{es}	nitrogen content in top soil (kg N/kg soil)
P_{ro}	phosphorus emitted through run-off to rivers (kg P/(ha y))
P_{rol}	quantity of P lost through run-off for a land use category (kg P/(ha y))
F_{ro}	correction factor for fertilization with phosphorus (dimensionless)
P_2O_{5min}	quantity of P_2O_5 contained in mineral fertilizers (kg P_2O_5/(ha y))
P_{er}	phosphorus emitted through erosion to rivers (kg P/(ha y))
P_{es}	phosphorus content in top soil (kg P/kg soil)
$M_{leach\ i}$	agricultural drainage related emission of the heavy metal i (mg metal/(ha y))
$m_{leach\ i}$	average amount of leaching of heavy metal i (mg metal/(ha y))
A_i	allocation factor heavy metal i (dimensionless)
$M_{agro\ i}$	input of heavy metal i from agricultural production (mg metal/(ha y))
$M_{deposition\ i}$	input of heavy metal from atmospheric deposition (mg metal/(ha y))
$M_{erosion\ i}$	heavy metal i emissions to surface water through erosion (mg metal/(ha y))
$C_{tot\ i}$	heavy metal i content of soil (mg metal/kg soil)
$M_{soil\ i}$	change in the content of metal i in the soil due to the agricultural system (mg metal/(ha y))
$Inputs_i$	total input of heavy metal i to the agricultural soil (mg metal/(ha y))
$Outputs_i$	total output of heavy metal i from agricultural soil (mg metal/(ha y))
SNB	soil nitrogen balance (kg N/(ha y))
N_Fert	nitrogen provided by fertilizers (kg N/(ha y))
N_Seed	nitrogen provided by sowing seed (kg N/(ha y))
N_AtDep	nitrogen provided by atmospheric deposition (kg N/(ha y))
N_FrLiv	nitrogen fixed by the effect of soil free living organisms (kg N/(ha y))
N_BioFix	nitrogen symbiotic biological fixation of legumes (kg N/(ha y))
N_HarvEx	nitrogen exported by the harvest (kg N/(ha y))
$N\_NO_3^-$	nitrogen losses by leaching in the form of NO_3^- (kg N/(ha y))
N_NH_3	nitrogen losses by volatilization in the form of ammonia (kg N/(ha y))
$N\_N_2O_{cr+Fert}$	nitrogen loses due to N coming from fertilizers and crop residues an emitted as N_2O (kg N/(ha y))
N_NO_x	nitrogen loses due nitrogen oxides released during the denitrification (kg N/(ha y))

Parameters

EF_1	IPCC factor 1, express the fraction of N from inputs that is emitted as N in form of N_2O (kg N-N_2O/kg N inputs)
EF_4	IPCC factor 4, express the fraction of N in form of NH_3 that is converted in N in form of N_2O (kg N-N_2O/kg N-NH_3)
EF_5	IPCC factor 5, express the fraction of N in form of NO_3^- leached and emitted as N in form of N_2O (kg N-N_2O/kg NO_3^-)
F_{rn}	enrichment factor for nitrogen (dimensionless)
F_{erw}	fraction of eroded soil that reaches the rivers (dimensionless)
F_{rp}	enrichment factor for phosphorus (dimensionless)
F_{rh}	enrichment factor for heavy metals (dimensionless)

0.43 kg N/(ha y). For top fertilization doses of 80 kg N/(ha y) the average GHG savings with respect to natural gas were 63.7% and the average non-renewable energy consumption was 6, 4 times less for the bioenergy system than for natural gas. Fossil energy accounted for more than 95% of total non-renewable energy in this calculation. This work evidences that determinate biomass growing conditions associated to high GHG savings and improved energy balances may cause detrimental effects for soil fertility due to considerable associated negative soil nitrogen balances. This finding suggests the convenience to include the soil nitrogen balance as a complementary indicator for bioenergy LCA calculations.

1. Introduction

The sustainable production of domestic biomass is a key issue to support the development of Bioeconomy and the Set Plan (Strategic Energy Research Plan), the two basic pillars for implementation of a low carbon economy in the EU objectives [1]. In this context, and in view of the limited residual biomass availability, the sustainability of the biomass value chains [2] from dedicated crops grown in the EU territory for the production of energy and bioproducts is being intensively studied in order to