



Possibilities for near-term bioenergy production and GHG-mitigation through sustainable intensification of agriculture and forestry in Denmark

Larsen, Søren; Bentsen, Niclas Scott; Dalgaard, Tommy; Jørgensen, Uffe; Olesen, Jørgen E.; Felby, Claus

Published in:
Environmental Research Letters

DOI:
[10.1088/1748-9326/aa9001](https://doi.org/10.1088/1748-9326/aa9001)

Publication date:
2017

Document version
Publisher's PDF, also known as Version of record

Document license:
[CC BY](#)

Citation for published version (APA):
Larsen, S., Bentsen, N. S., Dalgaard, T., Jørgensen, U., Olesen, J. E., & Felby, C. (2017). Possibilities for near-term bioenergy production and GHG-mitigation through sustainable intensification of agriculture and forestry in Denmark. *Environmental Research Letters*, 12(114032), [114032]. <https://doi.org/10.1088/1748-9326/aa9001>

LETTER • OPEN ACCESS

Possibilities for near-term bioenergy production and GHG-mitigation through sustainable intensification of agriculture and forestry in Denmark

To cite this article: Søren Larsen *et al* 2017 *Environ. Res. Lett.* **12** 114032

View the [article online](#) for updates and enhancements.

Related content

- [The global economic long-term potential of modern biomass in a climate-constrained world](#)
David Klein, Florian Humpenöder, Nico Bauer *et al.*
- [Reducing greenhouse gas emissions in agriculture without compromising food security?](#)
Stefan Frank, Petr Havlík, Jean-François Soussana *et al.*
- [Investigating afforestation and bioenergy CCS as climate change mitigation strategies](#)
Florian Humpenöder, Alexander Popp, Jan Philip Dietrich *et al.*

Environmental Research Letters



LETTER

OPEN ACCESS

RECEIVED
19 April 2017

REVISED
1 September 2017

ACCEPTED FOR PUBLICATION
29 September 2017

PUBLISHED
13 November 2017

Original content from this work may be used under the terms of the [Creative Commons Attribution 3.0 licence](#).

Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.



Possibilities for near-term bioenergy production and GHG-mitigation through sustainable intensification of agriculture and forestry in Denmark

Søren Larsen^{1,3,4} , Niclas S Bentsen¹, Tommy Dalgaard², Uffe Jørgensen², Jørgen E Olesen² and Claus Felby¹

¹ University of Copenhagen, Department of Geosciences and Natural Resource Management. Section for Forest, Nature and Biomass, Rolighedsvej 23, DK-1958 Frederiksberg C, Denmark

² Aarhus University, Department of Agroecology, Blichers Allé 20, DK-8830 Tjele, Denmark

³ Current affiliation: Danish Energy Association, Vodroffsvej 59, DK-1900 Frederiksberg C, Denmark

⁴ Author to whom any correspondence should be addressed.

E-mail: sla@danskenergi.dk

Keywords: bioenergy, GHG mitigation, sustainable intensification, biorefinery, renewable energy

Supplementary material for this article is available [online](#)

Abstract

To mitigate climate change it is necessary to further increase the deployment of renewable energy, including bioenergy. This analysis shows how this can be achieved in Danish agriculture and forestry before 2020. The key is a sustainable intensification and we show through three scenarios how it is possible to increase production while at the same time decreasing environmental impact and with only minor consequences on food and feed production. An additional ~10 Tg biomass can be available in 2020 for the Danish energy sector. By converting the biomass in a biorefinery concept it is possible to supply relevant, domestically produced energy carriers that amounts to ~5%–13% of 2020 Danish energy consumption. This has the potential to reduce the GHG emissions with 13%–21% of 2020 emissions. These results are possible because Danish net primary production and the human appropriation hereof can be increased. We show that biomass for bioenergy has a large near-term potential to supply relevant energy carriers to the society while at the same time achieving significant GHG emission mitigation.

Introduction

Accelerated deployment of renewable energy is key to mitigate climate change, and comprehensive scenarios for renewable energy suggest significantly increased use of biomass for energy [1–3]. Agriculture and forestry take part in that deployment, and the way we manage and extract energy, food and materials is potentially a very efficient tool for replacing fossil resources and mitigate greenhouse gas (GHG) emissions. An essential question is, if agriculture and forestry sustainably can support higher productivity to allow for harvest of energy and materials, while not jeopardizing other provisioning services from land use, such as food and feed production. Several bioenergy scenarios show increased GHG emissions, partly because of their indirect land-use change effect (iLUC) [4]. However, the effects of iLUC can be minimized through

sustainable intensification of existing agriculture and forestry.

Here we show how increased bioenergy production can be targeted through changes in management of rainfed, temperate agriculture and forestry. Bioenergy production can be substantially increased with reduced environmental impacts and only minor effects on food and feed production. Even though global net primary production (NPP) may constitute a planetary boundary for bioenergy production [5, 6] we show that its size can be increased, at least at a local scale, and that the human appropriation hereof (HANPP) may be sustainably increased. Denmark is used as an example of a temperate region country with intensively managed, mostly rainfed agriculture and forestry. This example may serve as inspiration for other non water-limited regions with intensively managed agriculture and forestry. Using Denmark as a model country has

Table 1. Description of main initiatives and assumptions of the three scenarios analysed in this study. More information about initiatives and assumptions is provided in the supplementary information available at stacks.iop.org/ERL/12/114032/mmedia. The table has been adapted from [9].

Scenario	Main initiatives and assumptions
REF—Reference development in biomass production and utilization according to historical trends.	<p>Agriculture</p> <ul style="list-style-type: none"> • No changes to species, cultivar or harvesting technology but the residual biomass (straw, livestock manure and perennial grass) are utilised. • Historical increase in yield, feed efficiency, area use for roads and towns, and organic farming included. • Export and import of cereal, soya, etc., are not included in the biomass potential. • Existing stands of perennial energy crops are projected. <p>Forestry</p> <ul style="list-style-type: none"> • 1900 ha afforestation per year. • Same species composition as existing forests. • Increased mobilisation of wood biomass but growth exceeds harvest.
BIO—Biomass production and use according to maximum biomass production while maintaining agricultural and forest production.	<p>Agriculture</p> <ul style="list-style-type: none"> • Conversion to cereal species producing 15% more straw. • Increased recovery of straw (15%) via modification of harvesting technology. • Oilseed rape on arable farms is replaced by sugar beet. • Grass yield in meadow areas are increased through fertilisation. • A cereal grain area the same size as that converted under the ENV scenario (approx. 149 000 ha) is converted to sugar beet. • Cover crops are utilised. <p>Forestry</p> <ul style="list-style-type: none"> • 1900 ha afforestation per year. • Extensive use of faster-growing tree species such as nurse trees. • The gains achieved from genetic improvements of trees are utilised. • Coniferous forests are regenerated with conifers and deciduous forests with 50% broadleaf, 50% conifers. • Greatly increased recovery of wood biomass to roughly the same size as growth.
ENV—As BIO but with additional concerns for reducing environmental impacts, in particular for reducing nitrate leaching from agricultural land.	<p>Same as Biomass-optimised, except for:</p> <p>Agriculture</p> <ul style="list-style-type: none"> • No straw removal from areas with critically low soil carbon content. • Increase in area with cover crops (81 000 ha). • Perennial energy crops replacing beet. • No cereals in areas with nitrate retention below 35%—instead perennial energy crops. • Meadow areas are not fertilised. <p>Forestry</p> <ul style="list-style-type: none"> • 4500 ha afforestation per year. • The gains achieved from molecular breeding of trees are utilised. • 47 000 ha deciduous woodlands more than 100 year old reclassified to conservation woodland. • Deciduous woodland is regenerated with broadleaves, and conifers in a 50:50 conifer to deciduous ratio. • Harvest of timber considerably less than growth.

the advantage of access to comprehensive data in the form of high quality statistics for land-use, crop yields and production, as well as extensive data on GHG emissions from land use change, production and conversion of biomass [7].

Material and methods

Three scenarios for the production and utilization of biomass for bioenergy from Danish agriculture and forestry by 2020 were developed [8, 9]. We applied a dynamic reference scenario (REF) projecting the current use of crops, observed yield trends and rate of urban sprawl and afforestation, and assumed increased

harvest rates in agriculture and forestry. A biomass focused scenario (BIO) models increased biomass production through selection of higher yielding crops and tree species, harvest rates equaling annual increments and harvest of currently unexploited biomass fractions. An environment focused scenario (ENV) combines higher biomass production with reduced nitrate leaching (e.g. by increased use of perennial crops), and increased biodiversity through e.g. more unmanaged forests. The scenarios and main assumptions are outlined in table 1. On the basis of these scenarios we analyzed the change from 2009–2020 in biomass and feed production, in energy production and the derived GHG emissions from fossil fuel substitution and changes in land use and management.

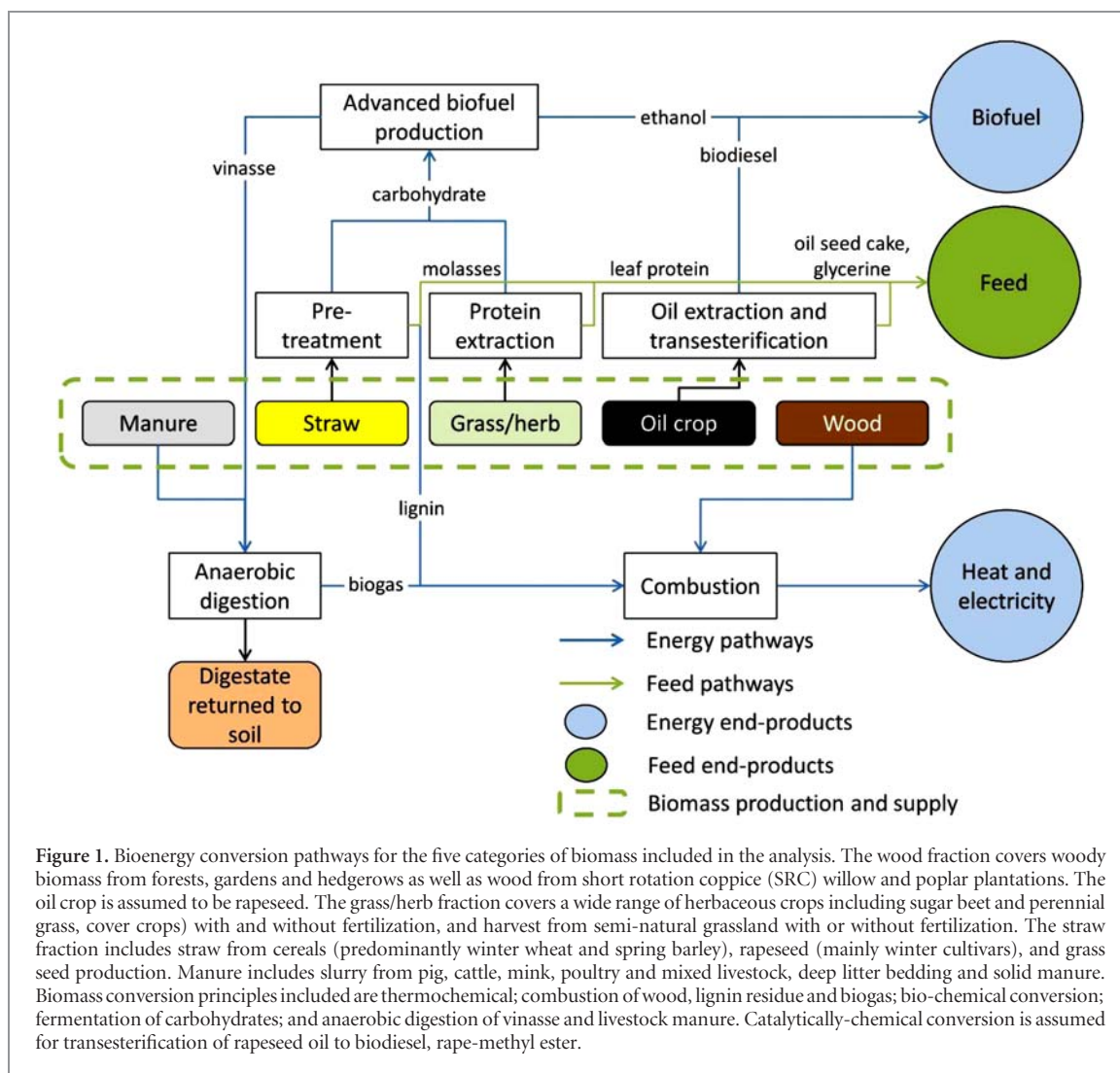


Figure 1. Bioenergy conversion pathways for the five categories of biomass included in the analysis. The wood fraction covers woody biomass from forests, gardens and hedgerows as well as wood from short rotation coppice (SRC) willow and poplar plantations. The oil crop is assumed to be rapeseed. The grass/herb fraction covers a wide range of herbaceous crops including sugar beet and perennial grass, cover crops) with and without fertilization, and harvest from semi-natural grassland with or without fertilization. The straw fraction includes straw from cereals (predominantly winter wheat and spring barley), rapeseed (mainly winter cultivars), and grass seed production. Manure includes slurry from pig, cattle, mink, poultry and mixed livestock, deep litter bedding and solid manure. Biomass conversion principles included are thermochemical; combustion of wood, lignin residue and biogas; bio-chemical conversion; fermentation of carbohydrates; and anaerobic digestion of vinasse and livestock manure. Catalytically-chemical conversion is assumed for transesterification of rapeseed oil to biodiesel, rape-methyl ester.

The production of biomass in each scenario is based on an extensive set of agricultural statistics on crop productivity and land use that have been used to estimate the productivity of all relevant crops for 2020 [7, 10]. The basis for these estimates is, in line with previous studies of decadal trends in Danish agriculture [7, 11], a linear extrapolation of present crop productivity as well as literature values when accurate statistics were not available. Underlying model assumptions and data references are further explained in the supplementary information.

Energy production builds on a biorefinery concept [12], and is founded on presently available technologies and conversion efficiencies for the years 2015–2020 [13]. The system boundaries for the analysis are set at the biorefinery or power plant, so there is no accounting of transmission and distribution losses. Each type of biomass is utilized in a specific conversion technology as shown in figure 1. This also allows for utilization of suitable parts of the biomass for producing livestock feed.

Straw and grass/herb biomass is converted bio-chemically in a bioethanol pathway. Production of oilseed crops is highly reduced in ENV and BIO

scenario, but used for bio-diesel and protein rich feed. Wood biomass is used for combined heat and power production (CHP) and livestock manure is utilized for anaerobic digestion into biogas and the remaining fraction is returned to soils as a fertilizer containing also recalcitrant carbon (C) that sustains soil C content.

The GHG emissions from agriculture consider methane (CH_4), nitrous oxide (N_2O) and C sequestered or emitted from soils because of land use change or change in agricultural or forestry management practices. These calculations are based on IPCC guidelines and observed yield and emission data from Danish agriculture combined with projections of the agricultural area [7, 14, 15]. In general, land-use change in the scenarios considers data on the land-use in 2009 and the proposed land use in the scenarios.

Quantification of GHG emission reductions from energy production builds on the assumption that additional biomass used for energy generation displaces one or more fossil fuels currently generating similar energy services. GHG emissions of current and alternative conversion routes are based on authoritative, generic references [16], or analyses specific to Denmark [13, 17, 18].

Table 2. Biomass appropriation for energy from five different biomass resources for each scenario compared to the situation in 2009. The protein rich feed that originates from biorefining of straw, grass and herbs is also shown and this can be used to substitute other animal feed sources.

Biomass resource	Scenario (2020)			
	2009	REF	BIO	ENV
	Tg dry matter			
Straw	1.62	2.92	3.47	3.27
Oil crops	0.13	0.21	0.11	0.02
Grass/herbs	0.00	0.28	5.14	3.97
Wood	1.67	1.57	2.32	1.73
Manure	0.18	2.57	2.57	2.44
Total	3.60	7.54	13.61	11.43
Protein rich feed (extracted from the total)			1.14	1.13

The feed production analyzed in the scenarios builds on an assumption of suitable biomass types being fractionated into edible and inedible parts [19]. This is suitable for grass and herbs, straw and oilseed biomass, whereas there is no edible fraction for wood or livestock manure.

Limitations

Our national analysis encompasses both the land/atmosphere and the energy system with assumptions related to the development of agricultural productivity, land-use and management as well as conversion efficiencies and GHG-emissions. The assumptions underlying this comprehensive analysis were to a great extent documented through other studies. The political and regulatory framework on both national and international level decides the ambition and tools for climate change mitigation in these sectors. Likewise, the market decides the prices of both agricultural and energy products as well as investments into energy infrastructure. The possible development of these surrounding socioeconomic factors is important for the implementation of the presented scenarios. The overall aim of this analysis is to show the potential in Denmark if all surrounding circumstances are beneficial for the development of a bioenergy sector.

Results

Biomass production potential

We find that it is possible, with current technology and by modified agricultural and forestry practices to supply additionally ~10 Tg of biomass for bioenergy in Denmark (table 2). In the REF scenario, with no optimizations of the agricultural production system, the biomass supply can be more than doubled from 3.6–7.6 Tg between 2009 and 2020. This is achieved primarily through increased mobilization of straw (+1.30 Tg) and livestock manure (+2.38 Tg) with a minor contribution from grass and herbs from marginal lands (+0.28 Tg).

Table 3. Increase in energy supply from domestically produced biomass to different energy end-uses. In % of gross Danish energy consumption in 2020 (high scenarios) [20].

Scenario	Biofuels	Heating	Electricity	Total
	% of gross energy consumption in 2020			
REF	1.1	2.9	1.3	5.3
BIO	3.1	8.6	1.4	13.1
ENV	1.9	6.8	1.3	10.0

The BIO scenario yields additionally 10 Tg compared to 2009 through increased mobilization of straw as well as new cultivars with lower harvest indices (+1.86 Tg), mobilization of livestock manure as in the REF scenario (+2.38 Tg), a major contribution from grass and herbaceous crops (+5.14 Tg), and some contribution from increased mobilization of forest biomass (+0.64 Tg).

Even when imposing further environmental restrictions on agricultural systems a considerable increase in biomass supply of 7.8 Tg can be achieved. Compared to the BIO scenario the ENV scenario supplies less straw (−0.21 Tg), less herbaceous crops (−1.17 Tg), and less forest biomass (−0.59 Tg). The contributions from forestry to increased biomass supply are, due to the short time horizon, mainly attributable to increased mobilization of resources already present.

Energy conversion potential

This analysis shows for a non-water limited agricultural system a large potential for increasing domestically and sustainably produced biomass to contribute to the future energy supply (table 3). In 2009, domestically produced biomass contributed 4.7% to the gross primary energy consumption. This fraction is increased in the REF scenario to 5.3%. Even under strict environmental constraints in the ENV scenario, the fraction is increased to 10.0% by 2020. When maximum bioenergy production is targeted, 13.1% of the gross domestic energy consumption can be provided for by biomass.

Potential changes to greenhouse gas emissions

Increased supply of bioenergy through deployment of a variety of changes in land and biomass management as suggested here holds a potential to provide feedstock that can displace fossil fuels and hereby contribute to national GHG emission reduction obligations. For this work, we have calculated GHG emission changes from two different processes: (1) GHG emissions savings from the displacement of fossil fuels with bioenergy, and (2) change in land use and management related emissions (CO₂, CH₄ and N₂O) between 2009 and 2020 in the different scenarios (table 4). Both the REF and BIO scenario result in reduced soil carbon content because of increased use of residues for bioenergy. In the ENV scenario the increased production of highly productive perennial crops will increase soil carbon storage slightly compared with current cereal crops (REF) (table 4). This rate of soil carbon uptake will

Table 4. Greenhouse gas emissions from land use and management change between 2009 and 2020. In addition: emissions from fossil fuel substitution in 2020 and the total emission as % of the projected Danish emissions in 2020. Negative values are reductions in emissions.

Scenario	Emissions from CH ₄	Emissions from N ₂ O	Emissions from soil C turnover	Total emissions from land use and management change	Effects of fossil fuel substitution	Sum of LU and management change and substitution	Change in total Danish emissions in 2020
	Tg CO ₂ eq. year ⁻¹						%
REF	-0.38	-0.20	0.32	-0.25	-5.9	-6.1	-13.2
BIO	-0.38	-0.43	0.43	-0.38	-9.5	-9.9	-21.4
ENV	-0.36	0.62	-0.19	0.07	-7.9	-7.8	-16.9

decrease over time after 2020 as a new steady state soil carbon level is approached.

The reduction in CH₄ emissions for all scenarios results from increased use of livestock manure for anaerobic digestion, thereby reducing CH₄ leakage from manure storages. In the REF and BIO scenarios N₂O emissions decrease by 0.20 and 0.43 Tg CO₂-eq year⁻¹, respectively. The grass crops in the ENV scenario are anticipated to be intensively fertilized, which has been shown not to enhance nitrate leaching [21] but estimated to significantly increase N₂O emissions in our scenarios. However, it may be possible to grow legumes or grass-legume mixtures with similar high yields and less N-fertilization. It may also be that the IPCC emission factor for N₂O formation from N-fertilization over-estimates the emissions from grassland [22]. There is a trade-off between increasing local NPP and N₂O emissions when the NPP increase is achieved through higher fertilization rates [23]. In total GHG emissions from land use change and management are reduced in the REF and BIO scenario but increased in the ENV scenario. Compared to GHG emission reduction achieved through fossil displacement, GHG emissions from land management and land use change are minimal (table 4). Therefore, increasing production from local, sustainable agriculture and forestry gives rise to only small changes in GHG emissions, but the increased production and mobilization of biomass to be used for bioenergy hold a considerable and lasting potential to reduce GHG emissions by substitution of fossil fuels.

The total, Danish GHG emissions in 2020 are projected to be 10.4 Tg CO₂-eq year for agriculture and approximately the same figures for both the transport and energy sector [24]. Thus, the magnitude of emission reductions shown in this study are of the same magnitude or slightly lower than emissions from any one of these sectors and between 13.2 and 21.2% of total Danish GHG emissions in 2020 (table 4).

Discussion

The total Danish land area of 4.3 Mha includes 2.6 Mha agriculture [7] and 0.62 Mha of predominantly managed forest [8]. The amount of biomass harvested from agriculture and forestry in 2009 was approximately

18 Tg dry matter of which 3.6 Tg was used directly for energy production [8].

A set of national energy and climate targets include a fossil free energy supply by 2050. Reaching this goal requires with projected developments in energy technologies a minimum of 192 PJ (~13 Tg) of bioenergy and organic waste out of a primary energy consumption of approximately 590 PJ [25]. The ~10 Tg additional biomass can be sourced via import, but for reasons of energy security and sustainability governance, we approach the analysis with a goal of national self-sufficiency and iLUC avoidance. Thus, the target is to supply an additional ~10 Tg of domestically produced biomass without reducing food and feed production or increasing land allocation to agriculture and forestry.

To analyze bioenergy production systems in the perspective of self-sufficiency and climate change mitigation it is necessary to select a set of conversion technologies. The chosen biomass to bioenergy conversion pathways target two relevant concerns: (1) End use sectors, where few or no renewable alternatives exist, i.e. liquid and gaseous fuels [26], and (2) a reduction in iLUC effects, achieved by using technologies that conserve food- and feed-grade protein [27]. Conversion of lignocellulosic biomass into advanced bioethanol, lignin and molasses [28] meets both concerns. Also production of biogas from manure and a range of crop residues have the sufficient flexibility to contribute to fuels for both transport and power generation [29]. A minor amount of the biomass (wood) is combusted to generate heat and electricity (figure 1). Wood gasification to transport fuels is not considered since this technology presently is not commercially available.

All initiatives presented are considered technically feasible and can be applied in other countries with similar land use, but climate and site specific options and constraints need to be considered.

It has been suggested that global NPP of natural vegetation constitutes an upper limit for biomass production [6] and that there is little room for expanding this limit. However, DeLucia *et al* [30] argued that, on a local scale, intensively managed production systems may be more productive than the local natural vegetation. There are also concerns that there are limits to the human appropriation of NPP (HANPP), although recent analyses show that the HANPP in Europe is as high as 43% against a global average of 25% [31]. Experimental studies in Denmark have shown that

biomass productivity can be increased substantially on agricultural land by changing from determinate crops as cereals, where production is constrained to a limited part of the potential growing season, into indeterminate perennial grass crops or annual crops with longer growing seasons [21, 32]. Although our analysis does not compare managed ecosystems with natural vegetation, it shows that there is considerable scope for increased local NPP. In the proposed scenarios increased NPP is combined with increased exploitation of NPP (HANPP) to supply additional biomass for energy services. At the same time other ecosystem services such as food/feed production and nutrient retention are maintained or improved and as such the scenarios can be seen as options for a sustainable intensification of agriculture and forestry targeting enhanced bioenergy supply while maintaining food production [8].

Soils and climate vary greatly across the globe, and even within Europe. Each local environment entails possibilities for smarter production of more biomass [33], which may be utilized for food, feed and bioenergy in an integrated manner as shown in this near-term study for Denmark. Development of biorefinery chains and processes to tap into this potential will be essential for utilizing a larger part of the NPP than presently [34].

A key issue for sustainably increasing local NPP and HANPP is the introduction of crops or cropping systems that utilize a larger part of the growing season and hereby a larger part of the solar energy influx. A change of food or feed producing land into bioenergy production may stimulate cultivation of new land for food and cause an increase in GHG emissions from land-use change [35, 36]. In 2009 approx. 44 000 ha were used for dedicated bioenergy production in Denmark. This area will increase to 144 000 ha in the REF scenario, to 337 000 ha in the BIO and 311 000 ha in the ENV scenario. The area used for dedicated food and feed production will thus decrease by 1.5%, 9.0% and 9.1%, respectively, compared to 2009 (see SI). However, food and feed production will not decrease correspondingly, because higher yielding crops combined with protein extraction allows for food production from the biomass before using other parts of the biomass for energy. If 10%–15% of the straw and grass biomass is extracted as feed in the optimized scenarios, the current food production can be sustained [8]. Accordingly, the combination of advanced conversion technologies and improved crop rotation schemes can reduce or even remove iLUC concerns, while sourcing biomass for energy.

Conclusion

Our case study for Denmark shows that there is a significant potential for sustainable biomass production by increasing NPP and HANPP on existing

agricultural land without reducing food production. With initiatives specifically selected for the cereal and livestock dominated Danish agricultural system, it is possible in the near term to reduce GHG emissions through increased fossil fuel substitution as well as reduced emissions associated with land use and management change.

Acknowledgments

This study was funded by the BIORESOURCE project funded by the Danish Council for Strategic Research. The authors appreciate the valuable inputs received from three anonymous reviewers.

ORCID iDs

Søren Larsen  <https://orcid.org/0000-0001-9260-7720>

References

- [1] Bruckner T *et al* 2014 Energy systems *Climate Change 2014: Mitigation of Climate Change Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O R Edenhofer *et al* (Cambridge: Cambridge University Press)
- [2] International Energy Agency 2013 *World Energy Outlook* (Paris: International Energy Agency)
- [3] US Department of Energy 2011 *US Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry* (Oak Ridge, TN: Oak Ridge National Laboratory)
- [4] Tonini D and Astrup T 2012 LCA of biomass-based energy systems: a case study for Denmark *Appl. Energ.* **99** 234–46
- [5] Running S W 2012 A measurable planetary boundary for the biosphere *Science* **337** 1458–9
- [6] Smith W K, Zhao M and Running S W 2012 Global bioenergy capacity as constrained by observed biospheric productivity rates *Bioscience*. **62** 911–22
- [7] Dalgaard T *et al* 2011 Developments in greenhouse gas emissions and net energy use in Danish agriculture—how to achieve substantial CO₂ reductions? *Environ. Pollut.* **159** 3193–203
- [8] Gylling M *et al* 2013 The +10 million tonnes study. Increasing the sustainable production of biomass for biorefineries *Frederiksberg: Department of Food and Resource Economics, Faculty of Science, University of Copenhagen*
- [9] Gylling M *et al* 2016 The + 10 million tonnes study: increasing the sustainable production of biomass for biorefineries (2016 updated edn) *Frederiksberg: Department of Food and Resource Economics, University of Copenhagen*
- [10] Harvest of Cereals etc 2017 (www.dst.dk/en/Statistik/dokumentation/documentationofstatistics/harvest-of-cereals-etc-#)
- [11] Hansen B, Thorling L, Schullehner J, Termansen M and Dalgaard T 2017 Groundwater nitrate response to sustainable nitrogen management *Sci. Rep.* **7** 8566
- [12] Cherubini F 2010 The biorefinery concept: using biomass instead of oil for producing energy and chemicals *Energ. Convers. Manage.* **51** 1412–21
- [13] Evald A, Hu G and Hansen M T 2013 *Technology Data for Advanced Bioenergy Fuels* (Copenhagen: Force Technology)
- [14] Tonini D, Hamelin L, Wenzel H and Astrup T 2012 Bioenergy production from perennial energy crops: a consequential LCA of 12 bioenergy scenarios including land use changes *Environ. Sci. Technol.* **46** 13521–30

- [15] Hamelin L, Jørgensen U, Petersen B M, Olesen J E and Wenzel H 2012 Modelling the carbon and nitrogen balances of direct land use changes from energy crops in Denmark: a consequential life cycle inventory *GCB Bioenerg.* **4** 889–907
- [16] Johansson T B, Patwardhan A P, Nakićenović N and Gomez-Echeverri L 2012 *Global Energy Assessment: Toward a Sustainable Future* (Cambridge: Cambridge University Press)
- [17] Wenzel H, Højbye L, Grandal R D, Hamelin L, Bird D N and Olesen A S 2014 *Carbon Footprint of Bioenergy Pathways for the Future Danish Energy System* (Copenhagen: COWI and University of Southern Denmark)
- [18] Nielsen C F B, Hassan A A, Herk-Hansen H and Ipsen K H 2010 *Lifecycle Assessment: Danish Electricity and Combined Heat and Power [in Danish: Livscyklusvurdering: Dansk el og kraftvarme]* (Fredericia: Dong Energy A/S, Energinet.dk, Vattenfall A/S)
- [19] Dale B E, Allen M S, Laser M and Lynd L R 2009 Protein feeds coproduction in biomass conversion to fuels and chemicals *Biofuels, Bioprod. Biorefin.* **3** 219–30
- [20] The Danish Energy Agency 2015 *Danish Energy and Climateprojections 2015 [in Danish Danmarks Energi- og Klimafremskrivning 2015]* (Copenhagen: The Danish Energy Agency)
- [21] Pugesgaard S, Schelde K, Larsen S U, Lærke P E and Jørgensen U 2015 Comparing annual and perennial crops for bioenergy production—influence on nitrate leaching and energy balance *GCB Bioenerg.* **7** 1136–49
- [22] Flechard C R *et al* 2007 Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe *Agric. Ecosyst. Environ.* **121** 135–52
- [23] Meyer-Aurich A, Olesen J E, Prochnow A and Brunsch R 2013 Greenhouse gas mitigation with scarce land: the potential contribution of increased nitrogen input *Mitig. Adapt. Strat. Glob. Change* **18** 921–32
- [24] Nielsen O-K *et al* 2014 *Projection of Greenhouse Gases 2011–2035: Aarhus University* (DCE–Danish Centre for Environment and Energy) p 137
- [25] The Danish Energy Agency 2014 *Energy Scenarios for 2020, 2035 and 2050* (Copenhagen: Danish Energy Agency)
- [26] Mathiesen B V, Lund H and Karlsson K 2011 100% Renewable energy systems, climate mitigation and economic growth *Appl. Energ.* **88** 488–501
- [27] Bentsen N S and Møller I M 2017 Solar energy conserved in biomass: sustainable bioenergy use and reduction of land use change *Renew. Sust. Energ. Rev.* **71** 954–8
- [28] Larsen J, Haven M Ø and Thirup L 2012 Inbicon makes lignocellulosic ethanol a commercial reality *Biomass Bioenergy* **46** 36–45
- [29] Mathiesen B V *et al* 2015 Smart energy systems for coherent 100% renewable energy and transport solutions *Appl. Energ.* **145** 139–54
- [30] DeLucia E H *et al* 2014 The theoretical limit to plant productivity *Environ. Sci. Technol.* **48** 9471–7
- [31] Plutzer C *et al* 2015 Changes in the spatial patterns of Human appropriation of net primary production (HANPP) in Europe 1990–2006 *Reg. Environ. Change* **16** 1225–38
- [32] Jørgensen U and Lærke P E 2016 Perennial grasses for sustainable european protein production *Perennial Biomass Crops for a Resource-Constrained World* ed S Barth, D Murphy-Bokern, O Kalinina, G Taylor and M Jones (Cham: Springer International Publishing) pp 33–41
- [33] Tilman D, Balzer C, Hill J and Befort B L 2011 Global food demand and the sustainable intensification of agriculture *Proc. Natl Acad. Sci.* **108** 20260–4
- [34] Parajuli R *et al* 2015 Biorefining in the prevailing energy and materials crisis: a review of sustainable pathways for biorefinery value chains and sustainability assessment methodologies *Renew. Sust. Energ. Rev.* **43** 244–63
- [35] Searchinger T *et al* 2008 Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change *Science* **319** 1238–40
- [36] Tilman D, Hill J and Lehman C 2006 Carbon-negative biofuels from low-input high-diversity grassland biomass *Science* **314** 1598–600