THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

BRIEFING

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Sustainability challenges of lignocellulosic bioenergy crops

The environmental sustainability of lignocellulosic energy crops is a key concern for low-carbon fuel policies. Policymakers generally agree that induced land-use change (ILUC) is a serious problem with food-based crops.[1] Since cultivating lignocellulosic energy crops such as *Miscanthus*, switchgrass, and short-rotation poplar also uses land, ILUC is a concern for these types of biofuel feedstocks as well. However, there isn't much agreement on how serious land-use problems are for energy crops, and whether the same kind of policy tools used to limit or account for ILUC from food-based biofuels should be applied.

This is an important question, because low-carbon fuel policies increasingly support the increased production of non-food feedstocks. For example, in the transport sector the European Commission has proposed an ambitious 2030 target for renewable

1 Low Carbon Fuel Standard: Final Regulation Order, California Air Resource Board, November 16, 2015. https://www.arb.ca.gov/regact/2015/lcfs2015/lcfsfinalregorder.pdf; European Union Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015 amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources, OJ L239, September 9, 2015, http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32015L1513; Oregon Clean Fuels Program, 340-253-0000, November 17 ,2017, https://secure.sos.state.or.us/oard/displayDivisionRules.action%3b?selectedDivision=1560; Energy Independence and Security Act of 2007, Public Law 110–140—DEC. 19, 2007, https://www.gpo.gov/fdsys/pkg/PLAW-110publ140/pdf/PLAW-110publ140.pdf

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energy from lignocellulosic and other non-food feedstocks,[2] so ambitious that it's difficult to see how that target could be met without energy crop biofuels.

This briefing paper summarizes the evidence on the environmental risks of lignocellulosic energy cropping and discusses whether it is necessary to incorporate sustainability criteria into policies promoting biofuels produced from energy crops in order to ensure that these biofuels meet the climate goals of low-carbon fuel policies.

IDENTIFYING THE ENVIRONMENTAL RISKS OF ENERGY CROPPING

There is a significant opportunity to produce low-carbon biofuels from energy crops under the right circumstances, but there is also a risk that doing so could lead to more environmental harm than good overall. There is no question that displacing forests with energy crops for biofuel would have a negative environmental and climate impact. There would be large carbon losses from cutting down trees, and this carbon debt would not be repaid within a reasonable timeframe of 20-30 years. Figure 1 shows the GHG emissions of biofuel made from energy crops that displace forest in different climates over a 20-year period; in each case, the biofuel would have a substantially greater climate impact than petroleum. This figure shows high emissions from biomass if forest land is cleared for energy crops, as well as foregone sequestration, which represents the lost opportunity for growing forests to continue to act as a carbon sink over time. Growing energy crops on land with high soil-carbon stocks, such as peatlands, or with high biodiversity would likely also have negative environmental consequences, although in some cases biomass production can help achieve conservation aims. Paludiculture, or growing crops in wetlands, can actually aid the preservation of peat grasslands for bird habitat.[3] In any case, it is clear that energy crops for biofuel production should not displace forest and should not be grown on peatlands or highly biodiverse lands without a clear environmental reason for doing so.

2 Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast), COM (2016) 767 final/2, February 23, 2017. https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_1.pdf

3 Reviewed in Stephanie Searle, Chelsea Petrenko, Ella Baz, Chris Malins. *Crops of the Biofrontier: in Search of Opportunities for Sustainable Energy Cropping* (ICCT: Washington, D.C., 2006). https://www.theicct.org/sites/default/files/publications/Energy%20Crop%20White%20Paper%20vF.pdf

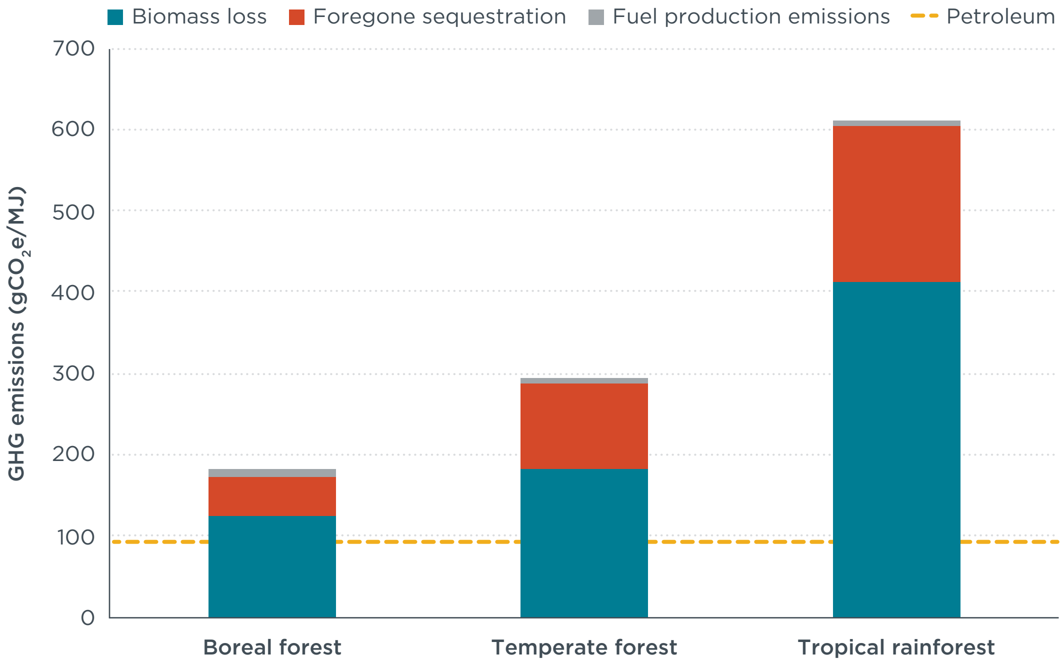

Figure 1. GHG emissions of biofuel produced from perennial grasses displacing forest in various climates compared to petroleum

Growing energy crops on recently-abandoned agricultural land has a more promising environmental outlook. Because there has not been sufficient time for much natural regrowth, there is little or no carbon debt to consider. Compared to leaving the land abandoned, energy cropping, particularly short rotation woody crops such as coppiced poplar or willow, may actually supply biodiversity benefits by providing heterogeneous habitats for wildlife. Growing energy crops on land contaminated by mining or other industrial activity almost certainly provides environmental benefits, because they can help rehabilitate contaminated land without displacing other uses of that land, but the available area of such land is limited. Energy crops may also provide a soil carbon benefit; energy crops sequester additional soil carbon when grown on agricultural land that has previously been used to grow annual crops.[4] However, soil carbon would be expected to increase over time on pasture or abandoned agricultural land even if that land is not used for energy cropping. Moreover, there isn't enough evidence available to reliably tell if soil carbon would increase faster under energy crops than if the land were left uncultivated.[5] Understanding the soil-carbon impact of energy cropping on abandoned land thus remains a key to understanding its full climate performance. Still, even in a worst-case scenario with no soil carbon benefit, energy crops grown on abandoned agricultural land would still deliver significant greenhouse gas (GHG) savings compared to petroleum (Figure 2).[6]

4 Ibid

5 Ibid

6 The assumptions and data sources used in Figure 1 and Figure 2 are provided in the Appendix.

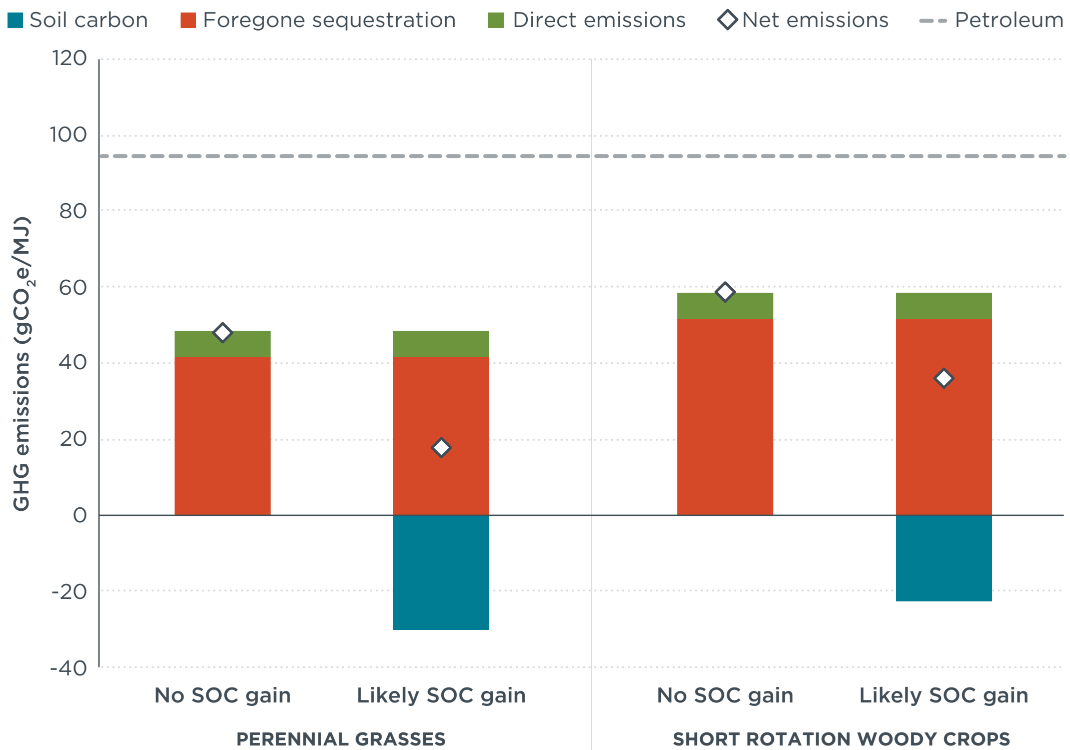

Figure 2. GHG emissions of biofuel produced from perennial grasses and short rotation woody crops grown on abandoned agricultural land in the EU, US, and Canada

If perennial energy crops are grown on existing agricultural land that would otherwise be used to grow annual food or fiber crops, energy crops would have soil carbon and biodiversity benefits compared to the crops they displace. However, by reducing the supply of the displaced food or fiber crops, energy cropping on existing agricultural land would lead to increased production of food or fiber crops on newly converted cropland elsewhere. This is the same problem with using food crops grown on existing agricultural land for biofuels. Diverting food crops from food and feed markets leads to a shortfall in supply that results in agricultural expansion onto forests, grassland, and other unused land.

The overall environmental performance of energy crops depends heavily on which types of land they are grown on: existing agricultural land, unused low-carbon stock land such as abandoned agricultural land, and high-carbon stock land such as forests. Economic forces largely determine where energy crops are grown, because farmers will only grow energy crops if it is more profitable to do so compared to growing other crops or leaving the land uncultivated. Economic modeling is typically used to predict where it would be economical to grow energy crops in response to a biofuel policy, and to forecast what the full global ILUC consequences of those decisions would be.

Economic studies on energy crop ILUC differ in their details, but it's clear that net land-use change emissions depend mostly on the amount of deforestation caused both directly and indirectly by energy crop demand (Figure 3). The methodology in one of the studies allows high deforestation using the Global Change Assessment Model (GCAM), and as a result predicts relatively high ILUC emissions for switchgrass, although still not as high as many ILUC estimates for food crops elsewhere using the same as well as other models. Another study, using the Food and Agricultural Policy Research Institute and Food and Agricultural Sector Optimization (FAPRI-FASOM) models, predicts a significant amount of deforestation as an indirect consequence of switchgrass displacing food and fiber crops on agricultural land; this study estimates a lower but still significant level of ILUC emissions. Most other well-known modeling studies, reviewed in Pavlenko and Searle (2018),[7] find that energy crops are not likely to displace food and fiber crops on agricultural land at a large scale, a finding that is consistent with our previous work showing that it is rarely more profitable to grow energy crops than food crops on good quality agricultural land.[8] Instead, these studies predict that most energy crops will be grown on abandoned agricultural land, fallow land, cropland-pasture, and other unused or lightly-used land with low-carbon stocks,[9] leading to estimates of low or even negative ILUC emissions when including soil carbon benefits.[10]

Figure 3. Share of net land expansion by land type in energy crop ILUC models and total land use change emissions from Pavlenko and Searle (2018)

The results from these modeling studies should not be interpreted to mean that energy crops have very low or negative ILUC emissions most of the time. Some of these studies are based on questionable assumptions and modeling choices. For example, the Global Trade Analysis Project (GTAP) model is incapable of predicting the direct or indirect conversion of large areas of forestland, and studies using the GTAP model and the Global Biosphere Management Model (GLOBIOM) use optimistic assumptions

7 Reviewed in Nikita Pavlenko and Stephanie Searle, *A Comparison of Induced Land-Use Change Emissions Estimates from Energy Crops* (ICCT: Washington, D.C., 2018). https://www.theicct.org/publications/comparison-ILUC-emissions-estimates-energy-crops

8 Chelsea Petrenko and Stephanie Searle, *Assessing the profitability of growing dedicated energy versus food crops in four European countries* (ICCT: Washington, D.C., 2017). https://www.theicct.org/sites/default/files/publications/EU-ILUC-Case-Studies_ICCT_nov2016.pdf

9 Various studies use different and often overlapping definitions of these terms.

10 Reviewed in Nikita Pavlenko and Stephanie Searle, *A Comparison of Induced Land-Use Change Emissions Estimates from Energy Crops* (ICCT: Washington, D.C., 2018). https://www.theicct.org/publications/comparison-ILUC-emissions-estimates-energy-crops

about soil carbon benefits.[11] While we still believe it likely that energy crops have lower ILUC emissions than food crops used for biofuel, there is a fair amount of uncertainty in the magnitude of energy crop ILUC emissions.

OPTIONS FOR RISK MITIGATION

Given the uncertainty of the net climate impacts of energy crops, a key question is whether regulatory controls and sustainability criteria are needed to ensure climate benefits from policies promoting energy crop biofuel. Since there is some disagreement in the literature regarding the distribution of land types on which energy crops would be grown, ranging from forest, unused low-carbon land, and existing agricultural land, we discuss possible measures to limit environmental damage on each land type separately.

The evidence consistently shows that biofuel produced from energy crops grown on recently-abandoned agricultural land in the EU, US, and Canada will deliver climate benefits because there is little or no carbon debt to consider and it may provide biodiversity benefits. It thus may not be necessary to impose sustainability criteria or other policy restrictions for the use of abandoned agricultural land or on low-carbon land contaminated by mining or other industrial activity.

One of the worst potential climate outcomes from energy crop derived biofuel would be direct conversion of forestland to energy cropping. The available evidence suggests that this is not likely to be widespread, but given the environmental risk, it may still be prudent to implement specific policy requirements preventing direct deforestation for energy cropping. Policies in the European Union currently contain sustainability criteria preventing the use of biofuel feedstock grown on recently converted high-carbon stock and highly biodiverse land, including forest.[12] If complied with, these criteria should be effective at preventing deforestation for energy cropping in the EU. The U.S. similarly prohibits use of forestland for biofuel feedstock production, but the U.S. Renewable Fuel Standard program lacks robust monitoring and enforcement mechanisms.[13]

It is not clear how great the risk is that energy crops will displace food and fiber crops on agricultural land, or how high the ILUC emissions of that outcome would be. It may thus be sensible to consider policy measures to limit the displacement of food and feed crops by energy crops. The Roundtable on Sustainable Biomaterials (RSB) and other

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11 Ibid.

12 These sustainability criteria apply to 2020 EU low-carbon fuel policies, including the Renewable Energy Directive (RED) and the Fuel Quality Directive (FQD), as well as a recast RED II for the period 2021-2030 that is currently in consideration by EU institutions. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, OJ L 140, April 23, 2009, http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0028; Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC, L 140/88, April 23, 2009, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0088:0113:EN:PDF; Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast), COM (2016) 767 final/2, February 23, 2017, https://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_1.pdf

13 Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program; Final Rule, 40 CFR Part 80, EPA–HQ–OAR–2005–0161, FRL–9112–3, March 26, 2010, https://www.epa.gov/renewable-fuel-standard-program/renewable-fuel-standard-rfs2-final-rule-additional-resources

groups have proposed criteria to reduce ILUC from biofuel feedstocks, such as the RSB's "Low ILUC Module." This module allows biofuels to receive a "Low ILUC risk" label if the feedstocks used are grown on unused land or are the result of yield increases. We have previously found these measures to be generally inadequate at preventing ILUC, at least for food feedstocks,[14] but they could be sufficient for energy crops. The most problematic option in RSB's module is to identify above-baseline yield increases as "low ILUC." This methodology would by definition label 50% of all existing crop producers as low-ILUC in a business-as-usual scenario. But because there is no large-scale production of lignocellulosic energy crops at present, no one is expected to use this option.

RSB's second main option to grow biofuel feedstock on low-carbon unused land is, to a lesser extent, also problematic for food crops because there is no assurance that the land would remain unused in the absence of biofuel demand. For example, if biofuel crops are grown on unused land in a region with expanding agricultural area, they could displace food crops that would otherwise have been grown on that land in the future. But again, this is unlikely to be a significant problem with lignocellulosic energy crops, at least at present. In countries that currently have or are considering greater incentives for cellulosic biofuel, such as the EU, US, and Canada, total agricultural area has remained roughly constant for the past several decades (Figure 4), and it is likely that most land that is currently unused will remain unused for the foreseeable future. Thus, RSB's Low ILUC Module could be largely effective at preventing the displacement of food and fiber crops by energy crops in these regions because food and fiber crops are not likely to be grown on currently unused land. These criteria could be further simplified to require only that no existing agricultural land be used for energy crops, since energy crops are unlikely to compete economically with other land uses such as urban development.

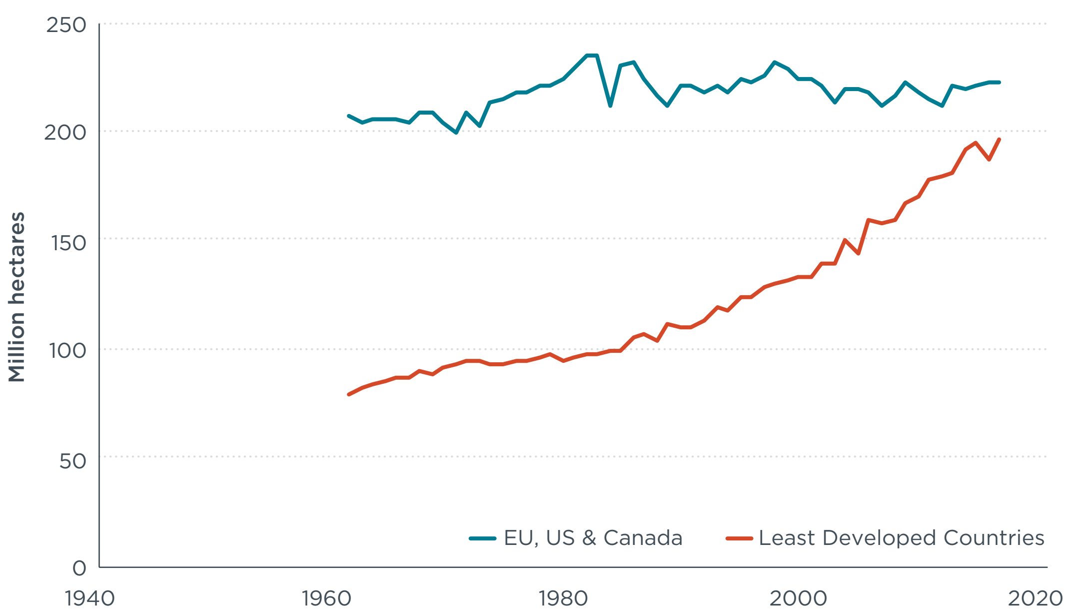

Figure 4. Total harvested crop area in the EU, US, and Canada over time compared to Least Developed Countries; data from the Food and Agriculture Organization of the United Nations

14 Sammy El Takriti, Chris Malins, Stephanie Searle, *Understanding options for ILUC mitigation* (ICCT: Washington, D.C., 2016). https://www.theicct.org/sites/default/files/publications/ILUC-Mitigation-Options_ICCT_nov2016.pdf

Because EU biofuel suppliers must already track feedstock at the farm level to comply with EU biofuel policies, creating a new requirement that energy crops not be grown on existing agricultural land should add only a negligible additional administrative and reporting burden on fuel and feedstock producers. The EU Parliament recently considered adding this requirement to its Renewable Energy Directive, proposing to exclude "energy crops produced on productive agricultural land" from counting towards the 2030 renewable energy in transport target, but the change was not adopted.[15] This proposal was a practical solution that would have substantially reduced the risk of negative environmental impacts from energy crop production.

It should be noted that this type of criterion would not be effective at reducing land use change emissions from food-based biofuels. The environmental impacts of growing annual food and fiber crops on abandoned agricultural land or other unused low-carbon stock land are significantly worse than for energy crops because conversion of these types of land to annual food crops result in substantial soil carbon and biodiversity loss.[16] Moreover, allowing the conversion of unused land to food crops in developing countries is more likely to displace expanding agricultural areas since food commodities can be sold and shipped internationally, making them more economically attractive to grow.

POTENTIAL SUSTAINABILITY CHALLENGES FOR THE FUTURE

While a prohibition against using productive agricultural land for energy cropping may be effective at reducing ILUC for energy crops in the near-term, it may not provide enough environmental assurance in future decades if energy crop production expands in the developing world. In the near term, energy crop production is likely to be confined to the EU and North America where policy incentives provide greater support for using the feedstock instead of food crops for biofuel, and potentially for renewable heat and power production. It would not likely be economical to grow cellulosic feedstock in developing countries that would be shipped to biorefineries in the EU and North America. Nor would it be likely for domestically processed biofuel to be shipped to developed countries. Outside of Brazil, which uses sugarcane bagasse to produce cellulosic ethanol, there are few prospects for building cellulosic biofuel facilities in developing countries at present.

If demand for energy crops in developing countries does rise in the future, a prohibition on the use of productive agricultural land for energy cropping may not be sufficient to limit ILUC. Agricultural land is still increasing in developing countries and is expanding rapidly in the world's Least Developed Countries according to the United Nations (Figure 4). There is thus a much greater chance in these countries that energy crops grown on unused low-carbon stock land would displace future

15 Of the Committee on the Environment, Public Health and Food Safety for the Committee on Industry, Research and Energy on the proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast), COM(2016)0767 – C8-0500/2016 – 2016/0382(COD), February 6, 2017; Amendments adopted by the European Parliament on 17 January 2018 on the proposal for a directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources (recast), COM(2016)0767 – C8-0500/2016 – 2016/0382(COD), January 17, 2018.

16 Reviewed in Stephanie Searle, Chelsea Petrenko, Ella Baz, Chris Malins. *Crops of the Biofrontier: in Search of Opportunities for Sustainable Energy Cropping* (ICCT: Washington, D.C., 2006). https://www.theicct.org/sites/default/files/publications/Energy%20Crop%20White%20Paper%20vF.pdf

crop expansion, which may in turn divert more food crop expansion onto high carbon stock land such as forest.

To be clear, there is little evidence to suggest that the ILUC emissions of this scenario would be substantial, and it is possible that the ILUC risk of such a policy in developing countries would be small. At the same time, available evidence does not provide assurance of low ILUC potential in these regions. Very few economic studies of ILUC have been conducted that model the effect of biofuel demand in developing countries. ILUC impacts are likely to be different depending on the country in which biofuel demand originates. This effect may be greater for energy crops than for food crops because increased demand for energy crops is unlikely to be met with increased imports due to high shipping costs. There is thus reason to believe that energy crops may have worse environmental consequences when grown in response to biofuel policies in countries with high carbon stocks and poor enforcement of deforestation bans, such as Indonesia.[17]

CONCLUSION

Lignocellulosic energy crops likely offer significantly greater climate and other environmental benefits when used for biofuel compared to most types of food crops, but they are not free from environmental risks. Policies containing simple sustainability criteria prohibiting the use of newly converted forestland and existing agricultural land for energy crop cultivation would be an effective and relatively low-burden measure to ensure positive environmental outcomes in developed countries. Indirect deforestation is a greater concern for growing energy crops on unused land in developing countries, and sustainability measures should be revisited if demand for energy crops in those countries becomes more widespread.

17 Anastasia Kharina, “Is Indonesia finally going in the right direction on palm oil?,” ICCT Staff Blog, 26 August 2016. https://www.theicct.org/blogs/staff/indonesia-in-right-direction-on-palm-oil

APPENDIX: NOTES ON METHODOLOGY

Table 1. Assumptions used in analysis for Figure 1 and Figure 2

Parameter	Assumption	Source
Timeframe for amortization	20 years	Same as in the Renewable Energy Directive
Perennial grass yield on abandoned agricultural land in temperate climate	10 tonnes per hectare per year	Roughly median yield for *Miscanthus* in Searle and Malins (2014)[a]
Short rotation woody crop yield on abandoned agricultural land in temperate climate	8 t/ha/y	Roughly median yield for willow and poplar in Searle and Malins (2014)
Energy crop yield in boreal climate	5.5 t/ha/y	Roughly median yield for *Miscanthus*, willow, and poplar in cold temperate climate in Searle and Malins (2014)
Energy crop yield in temperate and tropical climates	10 t/ha/y	Median yield for Eucalyptus in temperate and tropical climates in Searle and Malins (2014)
Biomass stock loss from forest conversion	50-300 tonnes per hectare	IPCC (2006)[b]
Carbon fraction of biomass	0.5	
Soil carbon change for perennial grasses grown on abandoned agricultural land compared to leaving land abandoned	0.55 tonne change per hectare per year	Soil carbon increase from Don et al. (2011)[c] minus median soil carbon increase on abandoned agricultural land from review in Searle et al. (2016)[d]
Soil carbon change for short rotation woody crops grown on abandoned agricultural land compared to leaving land abandoned	0.33 t C/ha/y	Soil carbon increase from Don et al. (2011) minus median soil carbon increase on abandoned agricultural land from review in Searle et al. (2016)
Foregone sequestration from re-growing biomass on previously forested land	1-7 t biomass/ha/y	Forest growth rates from IPCC (2006)
Foregone sequestration from re-growing biomass on abandoned agricultural land	1.5 tonnes biomass per hectare per year	Temperate forest growth rates from IPCC (2006); no foregone sequestration for reverting grassland; assumed proportion of reversion to forest/grassland reflects current split of natural land, using area-weighted ecotype distribution for US, EU, and Canada from World Wildlife Fund (2012)[e]
Biofuel yield	0.25 tonnes ethanol per tonne feedstock	Data used in Peters et al. (2015)[f]
Biofuel energy density	26.8 megajoules per kilogram for ethanol	UK Renewable Fuels Agency (n.d.)[g]
Carbon intensity of fossil fuel comparator	94.1 grams of CO_2 emissions per megajoule	EU (2015)[h]
Direct emissions of cellulosic ethanol production, including fuel processing, fuel and feedstock transportation, and electricity co-product credit	7.1 gCO_2e/MJ	Pavlenko et al. (2015)[i]

a Stephanie Searle and Chris Malins, "Will energy crop yields meet expectations?" *Biomass and Bioenergy*, 2014, 65: 3-12, https://www.researchgate.net/publication/260029711_Will_energy_crop_yields_meet_expectations
b Intergovernmental Panel on Climate Change (IPCC), "IPCC Guidelines for National Greenhouse Gas Inventories," Vol. 4: Agriculture, Forestry and Other Land Use. Chapter 4: Forest Land, (2006). http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_04_Ch4_Forest_Land.pdf
c Axel Don et al. "Land-use change to bioenergy production in Europe: implications for the greenhouse gas balance and soil carbon," *Global Change Biology Bioenergy,* 2011, 4: 372-391.
d Stephanie Searle, Chelsea Petrenko, Ella Baz, and Chris Malins, *Crops of the Biofrontier: in Search of Opportunities for Sustainable Energy Cropping* (ICCT: Washington, D.C., 2016:). https://www.theicct.org/sites/default/files/publications/Energy%20Crop%20White%20Paper%20vF.pdf.
e "Terrestrial Ecoregions," World Wildlife Fund, 2012. http:// worldwildlife.org/biome-categories/terrestrial-ecoregions
f Daan Peters, Sacha Alberici, Jeff Passmore, and Chris Malins, *How to advance cellulosic biofuels: Assessment of costs, investment options and required policy support,* (ICCT: Washington, D.C., 2015). https://www.theicct.org/sites/default/files/publications/Ecofys-Passmore%20Group_How-to-advance-cellulosic-biofuels_Dec2015.pdf.
g United Kingdom Renewable Fuels Agency, "Fuel chain default values spreadsheet"
h Council Directive (EU) 2015/652 of laying down calculation methods and reporting requirements pursuant to Directive 98/70/EC of the European Parliament and of the Council relating to the quality of petrol and diesel fuels, Official Journal of the European Union, 20 April 2015. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32015L0652.
i Nikita Pavlenko, Sammy El Takriti, Chris Malins, and Stephanie Searle, *Beyond the biofrontier: balancing competing uses for the biomass resource,* (Washington, D.C.: ICCT, 2015). https://www.theicct.org/sites/default/files/publications/ICCT_competing-uses-biomass_20160613.pdf

In Figure 2 we present a sensitivity analysis of the GHG performance of biofuel produced from energy crops grown on abandoned agricultural land in the EU, US, or Canada with varying assumptions about soil carbon impact because this is an influential parameter in the net GHG savings of energy crop biofuel. Another influential parameter is energy crop yield, which we further explore here. The GHG performance of biofuel produced from energy crops is worse with lower energy crop yields, because the GHG benefit of petroleum displacement per hectare is reduced as less biofuel can be produced per hectare. At low yields, the carbon penalty of foregone sequestration (which remains constant on a per hectare basis regardless of yield) exceeds the petroleum displacement benefit and the net GHG reduction from energy crop biofuel is negative. Conversely, with higher energy crop yields, the petroleum displacement benefit from producing more biofuel from the same area of land outweighs the foregone sequestration penalty by a greater amount, and the net GHG performance improves.

In Figure 5 we show how the GHG performance of energy crop biofuel varies with energy crop yields, in a worst-case scenario, assuming zero net soil carbon gain. With energy crop yields of 6 tonnes per hectare per yield, the GHG benefit of energy crop biofuel (i.e., the net GHG savings as a percent of petroleum) is low, and with yields lower than 5 t/ha/y, biofuels produced from energy crops grown on abandoned agricultural land would be worse for climate than fossil fuels. There is thus an environmental risk of worsening climate change if biofuels are produced from energy crops with very low yields.

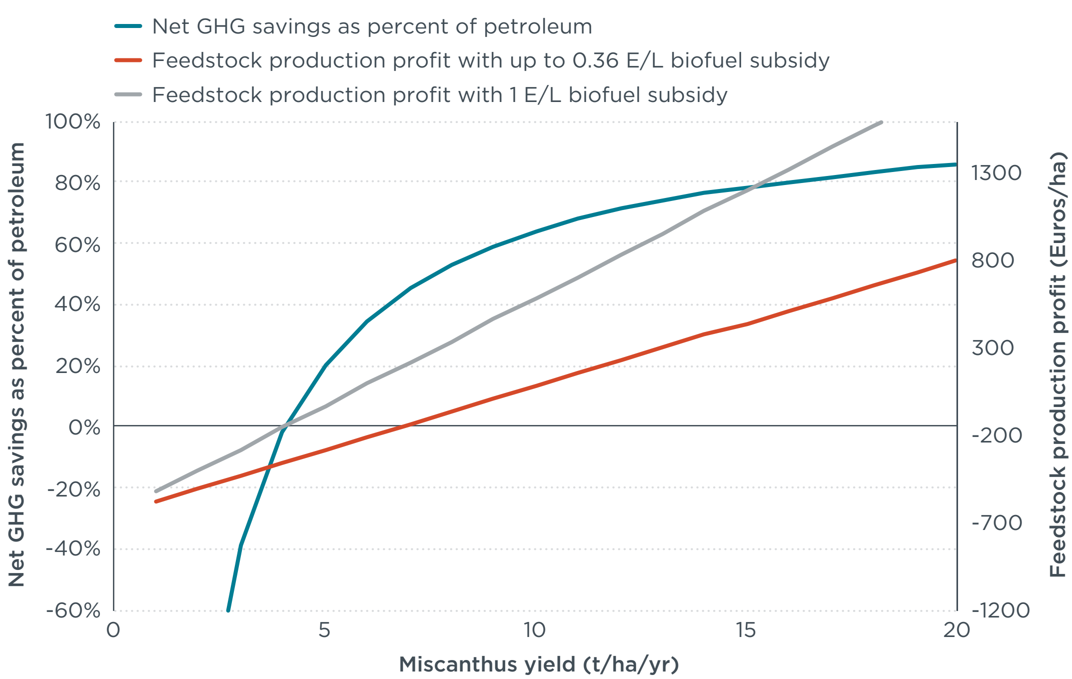

Figure 5. Net GHG performance of *Miscanthus* biofuel and feedstock production profit at two different biofuel subsidy levels with varying feedstock yield and zero net soil carbon gain

We further explore the likelihood that energy crops would be grown with such low yields. Figure 5 also shows how the profit margin of energy crop production varies with yield calculated using data for *Miscanthus* grown in Germany.[18] Because some feedstock production costs are fixed on a per hectare basis, costs per tonne feedstock produced are higher when fewer tonnes are produced per hectare, and costs per tonne decline with increasing yields. At current feedstock prices, energy crops are not profitable at yields lower than around 9 t/ha/y. It is thus unlikely that farmers will grow energy crops at yields low enough to lead to a poor climate outcome for the resulting biofuel.

If demands and incentives for cellulosic biofuel rise in future, feedstock prices could also rise and thus could make energy crop production profitable at lower yields. In a previous study on ultralow-carbon fuel production,[19] we found that, using the most economical type of cellulosic ethanol conversion technology—small bolt-on facilities adjacent to first generation ethanol plants that use crop residues as feedstocks—cellulosic ethanol would require policy support of at least $1.56 per gallon or €0.36 per liter of ethanol equivalent with current feedstock prices. The entirety of this incentive would be necessary to support the biofuel facility and the conversion process. With a €0.36 per liter subsidy, a cellulosic biofuel plant would still not be able to afford to pay more for feedstock than current prices, and, therefore, we would not expect the *Miscanthus* production profit to increase. If policy incentives exceed €0.36 per liter for cellulosic ethanol, the additional support could potentially support higher feedstock prices. Much of the additional incentive amount would likely be necessary to support more expensive forms of cellulosic biofuel conversion technology with better long-term scaling potential, as well as potentially greater feedstock and fuel transport costs as facilities are built in higher-cost locations.

In Figure 5, we show the profit margin of *Miscanthus* production with a higher subsidy level of €1.00 per liter. We note that this level of policy support is significantly higher than any incentive currently available for cellulosic ethanol in the US, EU and Canada. Even with such a high level of support, we find that energy crop production would not be profitable at yields lower than 5 t/ha/y. The assumptions used in this analysis are listed in Table 2. It is thus unlikely that energy crops will be grown at such low yields as to erase or reverse the climate benefit of the resulting biofuel. Additionally, as noted, the illustration in Figure 5 is based on a worst-case scenario assuming zero carbon gain from energy crops grown on abandoned agricultural land. If soil carbon gain is actually achieved, it is even more unlikely that energy crops could be grown under conditions resulting in biofuel with a poor GHG performance. Given the available evidence, we consider it highly likely that biofuel produced from energy crops grown on recently abandoned agricultural land in the EU, US, and Canada will deliver climate benefits compared to petroleum.

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18 Chelsea Petrenko and Stephanie Searle, *Assessing the profitability of growing dedicated energy versus food crops in four European countries* (ICCT: Washington, D.C, 2007). https://www.theicct.org/sites/default/files/publications/EU-ILUC-Case-Studies_ICCT_nov2016.pdf

19 Nikita Pavlenko, Stephanie Searle, and Brett Nelson, *A comparison of contracts for difference versus traditional financing schemes to support ultralow-carbon fuel production in California.* (ICCT: Washington, D.C.: 2017). https://www.theicct.org/sites/default/files/publications/CfD-Cost-Benefit-Report_ICCT_Working-Paper_vF_23012017.pdf

Table 2. Assumptions used in analysis for Figure 5

Parameter	Assumption	Source
EUR/USD exchange rate	0.87	
Minimum selling price for cellulosic ethanol to generate profit	$4.37 (€3.8) per gasoline equivalent gallon; $2.89 (€2.51) per ethanol equivalent gallon	Pavlenko et al. (2017)[a]
Market price for ethanol	$1.34 (€1.17) per gallon ethanol equivalent	Current futures price for ethanol (INO.com; CME group)[b]
Biofuel yield	0.25 tonnes ethanol per tonne feedstock	Data used in Peters et al. (2015)
Fraction of subsidy above €1.15/L that is passed on to feedstock producers	0.25	

a Nikita Pavlenko, Stephanie Searle, and Brett Nelson, *A comparison of contracts for difference versus traditional financing schemes to support ultralow-carbon fuel production in California.* (ICCT: Washington, D.C.: 2017). https://www.theicct.org/sites/default/files/publications/CfD-Cost-Benefit-Report_ICCT_Working-Paper_vF_23012017.pdf

b "Ethanol (CBOT:EH)," INO.com, Accessed December 15, 2017. http://quotes.ino.com/exchanges/contracts.html?r=CBOT_EH; "Ethanol Futures Quotes," CME group, Accessed December 15, 2107. http://www.cmegroup.com/trading/energy/ethanol/cbot-ethanol.html