OPINION

Can biomass supply meet the demands of BECCS?

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Abstract

In order to reach the reduced carbon emission targets proposed by the Paris agreement one of the widely proposed decarbonizing strategies, referred to as negative emissions technologies (NETs), is the production and combustion of bioenergy crops in conjunction with carbon capture and storage (BECCS). However, concerns have been increasingly raised that relying on the potential of BECCS to achieve negative emissions could result in delayed reductions in gross CO_2 emissions, with consequent high-risk of overshooting global temperature targets. We focus on two particular issues; the carbon efficiency and payback time of bioenergy use in BECCS and the potential constraints on the supply of bioenergy. The simplistic vision of BECCS is that one ton of CO_2 captured in the growth of biomass equates to one ton of CO_2 sequestered geologically, but this cannot be the case as CO_2 is emitted by variable amounts during the life cycle from crop establishment to sequestration below ground in geological formations. The deployment of BECCS is ultimately reliant on the availability of sufficient, sustainably sourced, biomass. The two most important factors determining this supply are land availability and land productivity. The upper bounds of the area estimates required correspond to more than the world's harvested land for cereal production. To achieve these estimates of biomass availability requires the rapid evolution of a multitude of technological, social, political, and economic factors. Here, we question whether, because of the limited sustainable supply of biomass, BECCS should continue to be considered the dominant NET in IPCC and other scenarios achieving the Paris targets, or should it be deemed no longer fit for purpose?

1. Introduction

Negative emissions technologies (NETs) are any process that removes carbon dioxide from the atmosphere and stores it in the biosphere or geosphere. In recent years, the international research on NETs has grown rapidly and publications have ranged in scope from reviewing the potential of NETs in climate change mitigation scenarios, to assessing the feasibility of achieving technological maturity and discussing deployment opportunities (Minx et al., 2017). However, concerns have been increasingly raised that ungrounded optimism in NETs potential could result in delayed reductions in gross CO_2 emission, with consequent high-risk of overshooting of global temperature targets (Kato & Yamagata, 2014; Fuss et al., 2014; Anderson & Peters, 2016; Vaughan et al., 2018). In order to reach the reduced carbon emission targets proposed by the Paris agreement, one of the widely proposed NETs is the production and combustion of forest products or second-generation bioenergy crops in conjunction with carbon capture and storage (BECCS). Most Integrated Assessment Models (IAMs) suggest that BECCS will make a significant contribution to NETs in the near to mid-term future and it has come to be viewed as the key CO_2 removal approach to keep global atmospheric CO_2 concentrations below 500 ppm and avoid catastrophic climate change (Fuss et al., 2018; Nemet et al., 2018; NAS, 2018). The reason why BECCS plays such a pervasive and pivotal role in climate change mitigation pathways is based on an assumption that large areas of land could be made available for bioenergy production at scale and that bioenergy is in the near term a relatively low-cost and low-emission source of energy (EASAC, 2018; Reid, Ali & Field, 2019).

Negative emissions as a consequence of BECCS is achieved when the CO_2 absorbed from the atmosphere during the growth cycle of biomass is released in combustion and energy production and then captured and stored indefinitely (Kemper, 2015). The simplistic vision of BECCS is that one ton of CO_2 captured in the growth of biomass equates to one ton of CO_2 sequestered geologically. However, biomass crops are not carbon neutral because GHG emissions are associated with the cultivation of biomass and furthermore GHG emissions occur throughout the BECCS value chain which reduces the carbon efficiency (Brandao et al., 2018; Tanzer & Ramirez, 2019).

Gough et al. (2018) identified a number of policy and governance challenges associated with the deployment of BECCS, including whether BECCS can be delivered at sufficient scale and also be provided sustainably. Here we suggest that it is becoming increasingly clear that the potential of BECCS is significantly constrained by a combination of socio-political, technical and geographic considerations, including limits to knowledge and experience (Fridahl & Lehtveer, 2018), and ask whether BECCS should continue to be the dominant NET in IPCC and other scenarios achieving Paris targets or should it be deemed no longer fit for purpose. We highlight two particularly important issues, the low carbon efficiency and long payback time of biomass for BECCS and the potential constraints on the supply of biomass for bioenergy.

2. Carbon efficiency of BECCS

The first impact of displacing fossil fuel with biomass for power generation in BECCS is a carbon debt derived from an increase in atmospheric CO_2 emission from land clearing and biomass production (*i.e.* direct land use emissions), harvesting, transport and processing (*i.e.* lifecycle emissions), as well as stack emissions due to higher CO_2 emissions from biomass combustions relative to continued fossil fuel use. The size of the bioenergy carbon debt depends also on how far upstream and downstream emissions are estimated within the system boundary of any life cycle analysis (LCA) (Tanzer & Ramirez, 2019). Studies including only a gate-to-gate boundary system ignore land-based emissions and assume that the amount CO_2 removed by biomass from the atmosphere is equal to the CO_2 emitted from its combustion (*i.e.* the bioenergy is ‘‘carbon neutral’’). These studies in general provide optimistic results on the potential savings from bioenergy crops. Since bioenergy systems involve land-based and lifecycle emissions, a further expansion of the boundaries is needed to encompass a ‘‘cradle-to-gate’’ boundary system which includes upstream emissions (Hastings, 2017, Roder et al., 2015). Ultimately, LCAs should include both upstream and downstream emissions in a ‘‘cradle-to-grave’’ determination of the overall climate mitigation of NETs (Tanzer & Ramirez 2019) (Figure 1).

Life cycle GHG assessments have shown that the differences in supply chain emissions from biomass cultivation, harvesting and transportation can be relatively small compared to the large differences in combustion and processing efficiencies of the power plants (Odeh & Cockerill 2008, Roder et al*.,* 2015). This is because, at the point of combustion, biofuels generate more CO_2 per unit of end-use energy than fossil fuels. Although woody biomass has approximately the same carbon intensity as coal (0.027 vs. 0.025 tC/GJ of primary energy), combustion efficiency of wood and wood pellets is in general lower than fossil fuels with typical combustion efficiencies for wood being approximately 25%, compared to 35% for coal (IEA 2016). Published estimates vary with the process examined, but energy processing losses for the wood pellet supply chain are on the order of approximately 27% if biomass is used in the drying process (Roder et al., 2015), compared to losses of approximately 11% for coal (IEA, 2016). In addition, capturing the CO_2 and then compressing it prior to transport produce an energy penalty that needs to be accounted for in the overall boundary system of BECCS. Additional energy is required to extract the steam needed for the CO_2 absorber/stripper system, to scrub the CO_2 due to compressing the flue gas and pumping the solvent, and finally to compress the recovered CO_2 prior to belowground storage sequestration.

3. Carbon payback time

The carbon payback time of biofuels is the number of years it can take to offset the carbon emissions generated by converting land for biofuels. Biofuels can only reduce atmospheric CO_2 over time by increasing net primary productivity above what it otherwise would have been. This period is very sensitive to the type of biomass crop and previous land use, and can range from less than 10 years for perennial grasses to over 100 years for slow growing clear-felled forests. Estimates of the payback time of biomass-fired power plants are limited, but have been reported as high as 400 years (Bentsen 2017). Depending on the land use change, the land-based production system and fossil fuel replaced, the payback time of the carbon debt of wood pellets is found to vary from 44 to >104 years to offset coal (Sterman et al., 2018). Pellets from residues are reported to have a temporal lags against coal-fired generation of approximately 16 years, while pellets from standing tree harvesting would require 35-50 years to reach a payback (McKechnie et al., 2011). It is also important to recognise that BECCS negative emissions are not delivered from year one and a time lag will occur before the initial extra emissions from producing the crop and establishing the BECCS facility are recovered.

4. Impacts of land use for BECCS

Land carbon stocks are influenced both by direct land use change (dLUC) involved in switching to the BECCS crop and from secondary impacts (*e.g.* in shifting demand for food to new areas) which lead to indirect land use change (iLUC). It is particularly difficult to summarize the potential emissions from iLUC, as its impact and extent is a function of spatial ecology, macro-scale economics, and type of biomass feedstock considered. So that iLUC can only be modelled and not measured directly. Second generation biofuels have been reported to have a median carbon loss of 5 gCO_2-eq/MJ, although sequestration is possible mainly in marginal areas, where perennial crops (such as switchgrass (*Panicum virgatum*), miscanthus (*Miscanthus x giganteus*) and *Arundo donax)* can increase below-ground carbon content leading to negative emissions of -12 gCO_2-eq/MJ (Valin et al., 2015). Pellets from forest residues have been reported to have a mean loss of 17 gCO_2-eq/MJ biofuel due to lower build-up of soil organic carbon stocks (Valin et al., 2015). Straw and stover could have losses varying from 2 to 3 gCO_2-eq/MJ biofuel (Overmars et al., 2015), while for cereal straw they vary from 0 to 16 gCO_2-eq/MJ biofuel (Valin et al., 2015) (see Table 1).

5. Balancing biomass supply and demand

The deployment of BECCS is ultimately reliant on the availability of sufficient, sustainably sourced, biomass for an active CCS industry operating at scale and a favourable policy and commercial environment to incentivise these investments (Boysen, Lucht & Gerten, 2017). IAM scenarios aimed at keeping warming below 2°C include global demand for sustainable biomass for BECCS ranging from 60 EJ/year up to more than 500 EJ/year (Fuss et al., 2018). The supply of biomass needs to be sufficient to either provide for centralised power stations or distributed energy systems, such as combined heat and power (CHP) stations. There are also opportunities to capture CO_2 from other sources such as ethanol biorefineries using first generation crops (Sanchez et al., 2018). The two most important factors determining the biomass supply for BECCS are land availability and land productivity. These factors are in turn determined by competing uses of land and a myriad of environmental and economic considerations (Searle & Malins, 2014). Published estimates of the potential for biomass supply vary widely, due mainly to the mixture of methodologies, assumptions and datasets employed (Batidzirai et al., 2012). Different estimates derive in part from differing utilisation of the same data collated by the Food and Agriculture Organisation (FAO), and from the use of different assumption on the spatial and temporal factors affecting biomass potential production. Furthermore, because in the FAO data-set there is a paucity of data for some regions, such as Africa, the lack of robust, reliable and high resolution information make global spatial biomass assessments difficult to model.

The potential sources of biomass for BECCS range from harvested residues from first generation food crops to forests, managed short-rotation coppice such as willow and poplar, and second generation biomass crops such as perennial rhizomatous grasses. The advantage of the second generation crops is that they can produce usable energy with less than 10% the energy inputs of first generation food crops, and lower water and nutrient requirements. However, the viability of achieving the highest yields demonstrated in experimental plots over large areas and many different types of soils has not yet been demonstrated. For example Searle & Mallins (2015) reviewed the yields of five major energy crops (*Miscanthus*, Switchgrass, Poplar, Willow, and Eucalyptus) all of which had produced high yields in small, intensively managed trials. However, yields were significantly lower in semi-commercial scale trials, due largely to biomass losses with drying and harvesting inefficiency under real world conditions.

Recent studies provide a large range for the global technical potential of biomass supply for 2050, ranging from ~30 to over 1,000 EJ/yr (Table 1). However the higher levels are considered implausible either because the estimates of available land are too optimistic or yield expectations are inflated by extrapolations from pilot-based studies to large areas of less productive marginal and severely degraded land (Smith & Torn, 2013; Smith et al., 2014). Furthermore the ability of degraded and marginal land to produce economic yields without the use of expensive fertilisers and irrigation is vastly overestimated (Field, Campbell & Lobell, 2007). In addition, relating the unevenly distributed biomass supply to the amount of CO_2 that can be stored geologically (Hendricks et al., 2004) is complex as the available regional information does not account for the possibility that CO_2 storage capacity may also be unevenly distributed within a given region (Muri, 2018).

The global land areas needed for the deployment of BECCS by 2100 have been estimated to range from 380 to 700 Mha (Smith et al., 2015). The upper bounds correspond to three times the world's harvested land for cereal production, twice the current water use for agriculture and 20 times the current US annual fertiliser use. The reason why the range is so large, revolves around differences in the definition of marginal land that is abandoned or severely degraded. Also, while there is evidence that the area of abandoned land has been increasing, with the FAO Landsat analysis indicating that across the tropics 77 Mha of cropland and pasture had been abandoned either temporarily or permanently during the 1990s (FAO, 2001; Gibbs et al., 2010), the productivity of this land is very low.

As well as abandoned land, it seems that globally there is a sizable area of land that is used for agriculture but which makes a small contribution to food production and could be used for biomass production (approximately 600 Mha) (Alexandratos and Bruinsma, 2012, Mason et al., 2015). Considering only low productivity cropland with terrain slope ≥20% (i.e. disadvantaged agricultural areas), Albanito et al. (2016) suggested that the global land suitable for bioenergy would be approximately 250 Mha, which could generate up to 318 EJ of primary energy.

Spatially explicit studies on the availability of biomass for BECCS are limited to the USA and UK. Baik et al., (2018) reported that by 2020 in the US up to 230 Mt of lignocellulosic biomass could be available annually producing as much as 400 Mt CO_2/year for sequestration in BECCS. The UK has a theoretical storage CO_2 capacity of 78 $GtCO_2$ with 50% confidence (Bentham et al., 2014), and previous research reported that BECCS could mitigate between 4.5 and 55 $MtCO_2$/year and approximately 1.5 Mha could be made available to bioenergy crops (ETI, 2016; Smith et al., 2016). However, considering only the low quality grade agricultural land available to produce an environmentally and economically sustainable supply of biomass to the power sector, Albanito et al. (2019) reported that only 0.4 to 0.5 Mha would be available across Great Britain.

6. Are biomass for BECCS ambitions sustainable?

In recent years the widely accepted criteria for a sustainable biomass supply have evolved to ensure that the biomass: (i) is not redirected from food or animal feed purposes, (ii) does not reduce the ecological functioning of the land, (iii) is grown on marginal land not suitable or economically attractive for food crop production, and (iv) is utilised locally (within ~50 km) to limit transport costs (Lewandowki, 2015).

Smith et al., (2015) make it clear that bioenergy systems deployment needs to balance a range of environmental, social, and economic objectives that are not always fully compatible. The effectiveness and consequences of bioenergy development depends on: (i) the technology used, (ii) the location, scales, and pace of implementation (iii) the land used, *i.e.* forest, grassland, crop lands, and marginal land, including how they displace existing land use, and (iv) the business models and practices adopted. The conclusion is that estimates of availability for the future depends on the evolution of a multitude of social, political, and economic factors including land tenure and regulation, trade, and technology (Smith et al., 2015; Bui et al., 2018).

An additional and rapidly emerging issue is the realisation that there will be competing demands for biomass to provide the feedstock of a rapidly growing bio-economy (Dahmen et al., 2019). Using biomass for energy is a high volume, low value operation while biomass used for the production of bio-based chemicals and materials, which will be essential if the demands to remove non-degradable plastics from the environment are to be met, has a much higher value.

We suggest that further work is thus required to quantify the sustainable capabilities for BECCS as a NET. This should demonstrate that, before being given priority in future climate change reduction strategies, the risks can be managed effectively through not only technical means but also international governance and the impacts that NETs will have on sustainable development goals and equity issues between nations (Fajady & Mac Dowell, 2017; Fuhrman et al., 2019). Moreover, energy policy should not overlook the inherently low efficiency of exploiting photosynthesis (the basic process driving conversion of CO_2 to biomass) for energy, since the amount of electricity which can be produced from a hectare of land using Photo Voltaic (PV) is at least 50-100 times that of biomass (Baldocchi & Penuelas, 2018). Reducing uncertainty in the outcomes is crucial to increase the robustness of decisions that use integrated assessment models as inputs and more sensitivity analyses should be made in order to understand the implications of various parameters and assumptions. Models to assess the impacts of biomass for BECCS on GHG concentrations and climate change require details of land use change impacts, including long term nutrient and productivity changes, supply chain emissions from biomass harvesting, processing, and transport, combustion efficiencies of and related emissions of different fuels, and changes in albedo and other biophysical processes that alter how GHGs affect the climate.

7. Conclusion

The International Energy Agency predicts that bioenergy could become the most important renewable energy by 2030 (IEA, 2016). However, this depends on the implementation of renewable energy strategies of key countries for the near-term deployment of BECCS at a scale to meet significant energy demands. The production of biomass feedstocks are directly linked to communities, farms, forests, and ecosystems from which resources are extracted. Therefore, bioenergy production for BECCS has potential for significant social and justice implications which could severely impede the deployment of BECCS at scale. This conflicts with the suggestion that BECCS may be an early-use NET, which allows time for the development of other more technically challenging NETs.

It is likely that NETs deployment at the huge scales envisaged in many scenarios could greatly exceed our collective ability to manage carbon cycle flows, thereby risking doing more harm than good. The viability of BECCS as a NET option depends on the choices made throughout the supply chain. Land competition for food production and greenhouse gas emissions associated with biomass cultivation, harvesting, and processing cast doubt on the ability of BECCS to result in net removal of CO_2 from the atmosphere. Assessment of water, land and carbon intensity of biomass supply chain and conversion technology is vital before supporting the large scale deployment of BECCS. Furthermore, the impacts of large scale BECCS on terrestrial biodiversity have received little consideration so far (Heck et al., 2018). All current evidence shows that the anticipated high variability in the effectiveness of BECCS CO_2 removal illustrates the need for a case by case analysis. The policy implication is that regulating and attributing value to these systems will have to be integrated to regional specificity, but how this might be achieved remains an open question (Reid, Ali & Field, 2019).

In conclusion, all available evidence points to a high variability in the possible outcomes of a BECCS project, both in terms of cumulative net carbon removal over the facility's lifetime, and also the time required for a given facility to start removing CO_2 from the atmosphere. Furthermore, significant risks exist of perverse outcomes where the net effect is to increase emissions (Fridahl & Lehtveer, 2018; Heck et al., 2018). Key factors which favour improved carbon efficiencies for biomass production are: limiting the impacts of direct and indirect land use changes, using carbon neutral power and organic fertilizers, prioritizing sea and rail over road transport, increasing the use of carbon negative fuels, and exploiting alternative biomass processing options; e.g. natural drying. However, the prospects of these achieving the anticipated negative emissions by BECCS in the near term are very uncertain and support the view that BECCS are not currently fit for purpose (Fuss et al., 2018).

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Table 1. Published estimates of global bioenergy technical production potential (*i.e.* amount of biomass energy that can be supplied globally given current expectations on technology, food demand and environmental constraints), and potential indirect land use change (iLUC) GHG emissions from the demand for food crops in new areas (iLUC) due to the conversion of current croplands to biomass feedstock production.

Reference	*Bioenergy Production Potential*	*Comments*
Haberl et al. (2010)	160-270 EJ/yr in 2050	'Scientific studies required in order to be more precise'
Dornburg et al. (2010)	200-500 EJ/yr in 2050	
Berndes et al. (2003)	100->400 EJ/yr in 2050	Review of 17 studies
Beringer et al. (2011)	130-270 EJ/yr in 2050	Used LPJmL DGVM model
Rogier et al. (2012)	793 EJ/yr currently	
Kemper et al. (2015)	50->1000 EJ/yr currently	'most likely range'
Fuss et al. (2018)	60-1548 EJ/yr in 2050	
Reference	*GHG emissions from iLUC*	*Production system*
Valin et al. (2015)	17 gCO_2-eq/MJ	Forest residues
Overmars et al. (2015)	2-3 gCO_2-eq/MJ	Cereal straw & stover
Valin et al. (2015)	0-16 gCO_2-eq/MJ	Cereal straw & stover
Valin et al. (2015)	-12 gCO_2-eq/MJ	Swichgrass & miscanthus
Melillo et al. (2009)	275-285 gCO_2-eq/MJ	Eucalyptus, swichgrass & poplar

Figure Legend:

Figure 1. The simplistic vision of BECCS is that one ton of CO_2 captured in the growth of biomass would equate to one ton of CO_2 sequestered geologically, which we can regard as a carbon efficiency of 1 (*i.e.* Gate to Gate with carbon neutrality). This simplistic concept of carbon neutrality in the bioenergy debate, however, is far from the reality. Depending on the different technology assessments boundaries applied to the BECCS scenario (*e.g.* Cradle to Grave), GHG emissions are emitted throughout the biomass supply-chain reducing the

carbon efficiency of BECCS to less than 50% (EASAC, 2018). In bioenergy systems, indirect land use change (iLUC) also needs to be included to achieve a full picture of the system impacts (*i.e.* Cradle to Grave with iLUC).