

RESEARCH REVIEW

Bioenergy for climate change mitigation: Scale and sustainability

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Abstract

Many global climate change mitigation pathways presented in IPCC assessment reports rely heavily on the deployment of bioenergy, often used in conjunction with carbon capture and storage. We review the literature on bioenergy use for climate change mitigation, including studies that use top-down integrated assessment models or bottom-up modelling, and studies that do not rely on modelling. We summarize the state of knowledge concerning potential co-benefits and adverse side effects of bioenergy systems and discuss limitations of modelling studies used to analyse consequences of bioenergy expansion. The implications of bioenergy supply on mitigation and other sustainability criteria are context dependent and influenced by feedstock,

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management regime, climatic region, scale of deployment and how bioenergy alters energy systems and land use. Depending on previous land use, widespread deployment of monoculture plantations may contribute to mitigation but can cause negative impacts across a range of other sustainability criteria. Strategic integration of new biomass supply systems into existing agriculture and forest landscapes may result in less mitigation but can contribute positively to other sustainability objectives. There is considerable variation in evaluations of how sustainability challenges evolve as the scale of bioenergy deployment increases, due to limitations of existing models, and uncertainty over the future context with respect to the many variables that influence alternative uses of biomass and land. Integrative policies, coordinated institutions and improved governance mechanisms to enhance co-benefits and minimize adverse side effects can reduce the risks of large-scale deployment of bioenergy. Further, conservation and efficiency measures for energy, land and biomass can support greater flexibility in achieving climate change mitigation and adaptation.

KEY WORDS

bioenergy, climate change, integrated assessment models, land, mitigation, sustainability

1 | INTRODUCTION

Bioenergy refers to energy derived from biomass or its metabolic by-products. Bioenergy accounts for about 10% of world total primary energy supply, including traditional use for heating and cooking ('traditional biomass'; IEA, 2020a). The contribution of modern bioenergy (i.e. excluding traditional biomass) to final energy use is about four times that from wind and solar PV combined (IEA, 2018). Bioenergy includes a wide range of feedstocks, conversion processes and products (see Supporting Information). Bioenergy can be combined with carbon capture and storage (BECCS) to achieve negative emissions. Large-scale BECCS features prominently in many mitigation scenarios, but is at an early stage of development (IEA, 2020b). According to (Consoli, 2019), five BECCS demonstration plants were operating in 2019 and collectively captured 1.5 Mt CO₂ per year.

The contribution of bioenergy to world primary energy supply is expected to grow substantially in future. Bioenergy can support decarbonization of electricity supply, providing balancing power to maintain grid stability as the contribution from solar and wind power increases (Li et al., 2020), complementing other balancing options such as battery storage and reservoir hydropower (Göransson & Johnsson, 2018). Liquid biofuels can play an important role in hard-to-abate transport sectors such as aviation and shipping. Expansion of bioenergy is included in many countries' Nationally Determined Contributions, which express their commitments under the Paris Agreement (FAO, 2019). Most mitigation pathways presented in the Intergovernmental Panel on Climate Change's (IPCC) Special Report on global warming

of 1.5°C (SR1.5), that evaluates threats and responses to limit warming to 1.5 or 2°C, rely heavily on carbon dioxide removal (CDR) strategies provided by afforestation/reforestation and BECCS (IPCC, 2019a; Rogelj et al., 2018). The SR1.5 report found that most pathways would require large areas of energy crops, ranging from about 3.2 to 6.6 Mkm² in 2100 (IPCC, 2018a).

The prospect of large areas of energy crops has stimulated debate about the possible adverse impacts of such widespread land use change on natural and human systems (Fuhrman et al., 2020; Smith et al., 2019, 2020). Previous studies have noted that bioenergy feedstock systems can be associated with a range of positive and negative environmental, social and economic effects that are context specific and depend on the scale of deployment, prior land use and carbon stocks, land type, bioenergy feedstock and management regime, and climatic region (Robledo-Abad et al., 2017). The IPCC Special Report on climate change and land (SRCCL; IPCC, 2019a), addressed greenhouse gas (GHG) fluxes in land-based ecosystems, land use and sustainable land management in relation to climate change adaptation and mitigation, desertification, land degradation and food security. Several chapters of the SRCCL assessed potential mitigation as well as possible effects of bioenergy and BECCS on a variety of sustainability goals (i.e. mitigation, adaptation, food security and management of land degradation and desertification).

In this paper, we summarize these effects on sustainability goals, while highlighting the specific contexts that result in positive or negative impacts. This paper expands on existing literature through its identification of the potential set of circumstances that could result in positive and negative effects, its consideration of a

broad range of bioenergy feedstocks, and its synthesis of several different strands of bioenergy literature. Section 2 motivates this synthesis, highlighting the role of bioenergy and associated land use in mitigation scenarios. Section 3 describes the co-benefits and adverse side effects by feedstock, management regime and prior land use. This section also discusses the significance of the scale and pace of expansion, as well as indirect land use change (iLUC). Section 4 describes the policy and governance context surrounding bioenergy and identifies policy options that could reduce risks of adverse outcomes. Section 5 concludes with a discussion of what is and is not known about bioenergy deployment and its effects on a variety of environmental goals.

2 | BIOENERGY USE IN MITIGATION SCENARIOS

Many of the more stringent mitigation scenarios presented in the fifth assessment report of IPCC-WG III (resulting in 450 ppm, but also 550 ppm CO₂e concentration by 2100) relied heavily on large-scale deployment of bioenergy and BECCS (Clarke et al., 2014). The IPCC SR1.5 report extended the AR5 mitigation pathway assessment based on new scenario literature (IPCC, 2018b). In this assessment, all analysed pathways limiting warming to 1.5°C with no or limited overshoot were found to use CDR either to compensate for emissions from difficult to mitigate sources and/or to achieve net negative emissions enabling a return to 1.5°C after a temperature overshoot (Rogelj et al., 2018). Some pathways relied more on BECCS, while others relied more on reforestation/afforestation, which were the two CDR methods most often included in integrated pathways modelled for the IPCC SR1.5 report (IPCC, 2018b). These pathways are developed using Integrated Assessment Models (IAMs), which link biophysical models of biosphere and atmosphere processes with socio-economic models, and are applied to explore scenarios of the future evolution of global energy, land, economy and climate (Clarke et al., 2014; Riahi et al., 2017; van Vuuren et al., 2011; Weyant, 2017).

In the IPCC SR1.5 report (IPCC, 2018b), modelled bioenergy use was substantial in 1.5°C pathways with or without BECCS due to its multiple roles in decarbonizing energy supply (full range: 40–310 EJ year⁻¹, primary energy, in 2050; Rogelj et al., 2018). Most bioenergy in 1.5°C pathways is used in combination with CCS. In pathways where CCS is unavailable, bioenergy use remains high and can even exceed use in pathways with CCS, due to its versatility as an energy carrier (Köberle, 2019) and because limiting CCS results in increased carbon prices and increased deployment of non-fossil energy options like bioenergy (Muratori et al., 2016). The SR1.5 report showed that if bioenergy is strongly limited, IAMs typically favour BECCS options with high CO₂ capture rates (i.e. electricity generation). If bioenergy

is plentiful, IAMs tend to choose biofuel options with lower carbon capture rates but high value for replacing fossil fuels in transport (Bauer et al., 2018; Rogelj et al., 2018).

Several model assumptions can influence simulated bioenergy use (Köberle, 2019; van Vuuren et al., 2018). Most IAMs constrain the technical and economic potential of biomass production, as a way of reflecting biophysical limits and concerns about sustainability impacts (Calvin et al., 2014; van Vuuren et al., 2015). This can be done in different ways, for example, some scenarios include incentives for terrestrial carbon storage (Calvin et al., 2014; Humpenöder et al., 2014) or protected land areas (Calvin et al., 2014, 2019; Humpenöder et al., 2018; van Vuuren et al., 2015). Other important model assumptions include the cost and availability of fossil fuels (Calvin et al., 2016), the cost and availability of other mitigation options (Calvin et al., 2014; Gambhir & Tavoni, 2019; Köberle, 2019; Realmonte et al., 2019; van Vuuren et al., 2018), rates of technological change including agricultural yields (Creutzig, 2016; Popp et al., 2017), socio-economic conditions such as food demand (Popp et al., 2017), and policy (Calvin et al., 2014; Humpenöder et al., 2018; Reilly et al., 2012). As an example of the latter, mitigation scenarios generated by IAMs mostly assume a globally harmonized carbon price is applied evenly to all CO₂ emissions produced within the energy system (Butnar et al., 2020). However, while IAMs track all changes in carbon associated with biomass production and use for energy (including land use change), most scenarios assume that the biogenic carbon flows (e.g. carbon sequestration in biomass plantations and carbon emissions from biofuel combustion) are not included in carbon pricing regimes. This assumption stems from the way IAMs account for emissions associated with biomass (see Section 4.1). Studies have shown that this assumption has a strong effect on bioenergy deployment. For example, Calvin et al. (2014) explored several policy approaches to price biogenic carbon flows (both sequestration and emissions) and found that these approaches reduced bioenergy use. Similarly, most IAMs account for the emissions associated with the manufacturing of a technology in the industrial sector; those emissions are included in the carbon pricing regime for the industrial sector only. At the point of use of the technology, most IAMs only include in the carbon pricing regime the direct emissions associated with the operation and energy supply of the technology (Mendoza Beltran et al., 2020; Pehl et al., 2017; Portugal-Pereira et al., 2016). For example, the emissions associated with manufacturing solar photovoltaics are tracked and priced in the industrial sector in most IAMs. However, in the electricity sector, IAMs treat solar photovoltaic as a zero emissions technology in climate policy scenarios, despite the fact that there are some emissions associated with manufacturing.

The deployment of BECCS as a CDR measure in stringent mitigation pathways has become less dominant since

AR5, due to (i) a broader range of underlying assumptions about socio-economic drivers and associated energy and food demand; (ii) incorporation of a larger portfolio of mitigation and CDR options; (iii) targeted analysis of deployment limits for specific CDR options, such as BECCS, afforestation/reforestation, biochar and soil carbon management; and (iv) inclusion of a broader range of sustainability considerations.

The SR1.5 report (IPCC, 2018b) found that implementation of mitigation response options, limiting warming to 1.5 or 2°C, would require conversion of large areas of land for afforestation/reforestation and bioenergy crops. The SRCCL report (IPCC, 2019b) considered the implications of this scale of land use change. The change of global forest area in mitigation pathways ranges from about -0.2 to $+7.2$ Mkm² between 2010 and 2100, and the land demand for energy crops ranges from about 3.2 to 6.6 Mkm² in 2100 (Shukla et al., 2019). For comparison, the total global areas of forests, cropland, pasture and grazed savannahs and shrubland (in 2015) are in the SRCCL estimated at about 40, 15.6, 27.3 and 21 Mkm² respectively (IPCC, 2019a).

These estimates are affected by several limitations of IAMs in their representation of biomass and biomass deployment: (1) limited number of feedstock/management practices; (2) limited representation of land quality; and (3) limited representation of institutions, governance and local context. In terms of feedstock/management practices, IAMs include only a subset of potential feedstock/management practices. They typically include purpose-grown biomass (including sugar, starch or oil crops and lignocellulosic crops such as miscanthus and short-rotation woody crops), agricultural and forestry residues, and traditional biomass (Hanssen et al., 2019). It is difficult to represent biomass production integrated with agriculture in IAMs, such as in biomass-crop-livestock systems, agroforestry or double-cropping, due to coarse temporal and spatial resolution. With respect to forest systems, reforestation and afforestation have generally been modelled as forests managed for carbon sequestration alone, rather than managed for biomass production, such as for wood products. Land use for biomass production and for carbon storage have thus been modelled as mutually exclusive mitigation options in IAMs, though some sectoral models have evaluated these practices simultaneously (Baker et al., 2019; Doelman et al., 2020; Harper et al., 2018). In addition, by necessity in global modelling, the growth rates of biomass crops are modelled according to plant functional types that aggregate species and simplify management regimes. For land quality, while model projections identify locations of biomass crops, albeit at low resolution (Bauer et al., 2018), they do not consider the current condition of available land (as influenced by historical land use), and how establishment of different energy cropping systems might improve or degrade land condition (see Section 3), which has implications for current and future productivity and the GHG mitigation

potential of bioenergy. Similarly, changes in soil quality as a result of harvesting a larger share of above-ground biomass are, at best, coarsely represented. Finally, IAMs often neglect governance (Köberle, 2019) and local context, including existing energy and industry infrastructure and policies, which affect both implementation rate and type of bioenergy systems implemented (Brown et al., 2019; Butnar et al., 2020).

Integrated Assessment Models have been used to investigate how bioenergy potentials and deployment, and the mitigation achieved, depend on the development of factors, including technology availability and cost, agriculture yields and food consumption patterns (Bauer et al., 2018; Daioglou, Rose, et al., 2020; Popp et al., 2014, 2017). But it has not been possible to confidently narrow down the implications of such factors, due to several uncertainties. There is uncertainty in the potential future yield of bioenergy crops, as well as the effect of land use change on vegetation and soil carbon stocks resulting from bioenergy deployment (El Akkari et al., 2018; Haberl, 2013; Whitaker et al., 2018). Moreover, there is large uncertainty as to the impact of climate change on biomass production (Smith et al., 2019) and this effect is excluded from most modelled pathways (IPCC, 2019a). There is also uncertainty on the demand for other land-based products, like food, which influences—and is influenced by—bioenergy deployment (Kalt et al., 2020). Besides assumptions influencing biomass production and land carbon stocks, models differ in their assumptions about energy conversion efficiencies, the cost of bioenergy and other technologies, and the cost of, potential of and constraints on CCS (Daioglou, Rose, et al., 2020; Muratori et al., 2020).

Recent studies also indicate a discrepancy between IAMs and other models with respect to the effect of bioenergy on terrestrial carbon uptake. For example, Harper et al. (2018) and Krause et al. (2018) found much lower total carbon uptake potential when land use maps from IAMs were combined with dynamic global vegetation models (DGVMs), than was predicted in the original IAM calculations, possibly due to lower energy crops yields and differences in soil carbon cycle responses upon land conversion estimated with the DGVMs than the original IAM. In contrast, Li, Ciais, et al. (2020) suggest that IAMs underestimate energy crop yields. Illustrating the importance of policy design and land management responses, Favero et al. (2020) use a forest economic model to show that increased bioenergy demand increases forest carbon stocks through afforestation activities and more intensive management relative to a no-bioenergy case, but also results in conversion of natural forests to more intensive management, with potential biodiversity losses. Incentivizing wood-based bioenergy and forest carbon sequestration simultaneously was found to increase carbon sequestration and conserve natural forests. Baker et al. (2019) find a similar complementarity between forest carbon sequestration and bioenergy.

Due to these uncertainties and diverging assumptions, there is low agreement across models and scenarios as to the quantitative effect of bioenergy and BECCS on atmospheric GHG concentrations or the amount of bioenergy and BECCS needed to limit warming to a particular level (Muratori et al., 2020). Due to the missing elements and uncertainties identified above, caution should be applied in interpreting the results of IAMs with respect to the area of energy crops required to meet a particular climate target and the impacts of this scale of deployment. Alternative ways of assessing the mitigation potential and impacts on other sustainability indicators can provide complementary insights. For example, methods which derive the marginal impact of bioenergy deployment under specified spatial, technological and socio-economic conditions (Daiglou et al., 2017; Hanssen et al., 2020; Kalt et al., 2020; Staples et al., 2017).

3 | THE POTENTIAL CO-BENEFITS AND ADVERSE SIDE EFFECTS OF BIOENERGY SYSTEMS

The production and use of biomass for bioenergy can have implications for emissions and mitigation potential, as well as co-benefits, adverse side effects, and risks, with respect to adaptation, land degradation, food security, biodiversity, water scarcity and other sustainable development goals. The sign and magnitude of these effects depend on a variety of factors (Robledo-Abad et al., 2017), including the feedstock (Carvalho et al., 2016; Davis et al., 2013; Del Grosso et al., 2014; Qin et al., 2016; Searchinger et al., 2017), management regime (Carvalho et al., 2016; Davis et al., 2013; Del Grosso et al., 2014; Hudiburg et al., 2015; Jans et al., 2018; Qin et al., 2016; Silva-Olaya et al., 2017; Whitaker et al., 2018), climatic region (Jans et al., 2018; Qin et al., 2016; Whitaker et al., 2018), other demands for land (Alexander et al., 2015), and scale of deployment (Popp et al., 2017).

The mitigation value of bioenergy depends on the effect on energy system emissions (a function of the bioenergy product, conversion plant configuration including whether CCS is used, energy conversion efficiency and the emissions intensity of the energy carriers being displaced; Cherubini et al., 2009; Hanssen et al., 2020; Searchinger et al., 2017) as well as land carbon balances (Cherubini et al., 2009; Hanssen et al., 2020; Searchinger et al., 2017), non-CO₂ emissions (Cherubini et al., 2009) and biophysical effects resulting from land-atmosphere interactions (e.g. surface albedo, evapotranspiration, etc.; Zhu et al., 2017), which, in turn, depend on the type of feedstock (Carvalho et al., 2016; Cherubini et al., 2009; Davis et al., 2013; Del Grosso et al., 2014; Qin et al., 2016; Searchinger et al., 2017), management practice (nitrogen fertilizer application, irrigation, etc; Carvalho et al., 2016; Cherubini et al., 2009; Davis et al., 2013; Del Grosso

et al., 2014; Hudiburg et al., 2015; Jans et al., 2018; Qin et al., 2016; Silva-Olaya et al., 2017; Whitaker et al., 2018), the land area requirement (Hanssen et al., 2020) and its influence on other land use and vegetation cover (Cherubini et al., 2009; Hanssen et al., 2020; Searchinger et al., 2017). The net effect on atmospheric GHG concentrations also depends on co-product output and associated displacement effects, and how the bioenergy products contribute to energy system transformation (Cowie et al., 2019). Bioenergy can result in anywhere from a net reduction in emissions (i.e. a beneficial mitigation effect), if a reduction in energy system emissions is combined with terrestrial carbon sequestration and low non-CO₂ emissions, to a net increase in emissions (i.e. an adverse effect on mitigation) if the land use emissions outweigh any associated reductions in energy system emissions (Haberl, 2013; Marland & Schlamadinger, 1997; Schlamadinger & Marland, 1996); noting also that the effect on mitigation is separate from the effect on other dimensions of sustainability.

In this section, we assess the sustainability implications of a range of bioenergy feedstocks, including the effect of different management regimes and prior land use. We also discuss the implications of the scale of deployment, the pace of expansion and iLUC.

3.1 | Effects by feedstock

Implications of different bioenergy feedstocks for mitigation, adaptation, land degradation, food security, water quality, biodiversity and a variety of other ecosystem services are summarized in Table 1 and discussed briefly. More detail of each feedstock is provided in the Supporting Information. We consider only biomass derived from agriculture and forestry and exclude processing residues and organic waste.

3.1.1 | Land carbon balance

The effect of purpose-grown feedstocks on site-level terrestrial GHG emissions depends on the specific feedstock, prior land use and management practice. The effect on atmospheric GHG concentrations in addition depends on whether the deployment of purpose-grown feedstocks cause iLUC with resulting GHG emissions (see Section 3.3). Perennial grasses and woody crops have higher biomass carbon stocks than annual crops, and can enhance soil carbon sequestration when planted on land previously cultivated with annual crops (Bárcena et al., 2014; Bolinder et al., 2020; Chadwick et al., 2014; Del Grosso et al., 2014; Dondini et al., 2009; Immerzeel et al., 2014; Mello et al., 2014; Milner et al., 2016; Robertson, Zhang, et al., 2017; Rowe et al., 2016; Schröder et al., 2018; Walter et al., 2015; Whitaker et al.,

TABLE 1 Implications of bioenergy feedstocks on Mitigation (M), Land Degradation (L), Food Security (F), Water (W) and Biodiversity (B) as influenced by Prior Land Use and by Management Regime. Positive indicates benefits; negative indicates adverse side effects; 'n.e.' indicates no effect; blank cells indicate a lack of literature

Feedstock	Prior land use and/or management practice	New management regime	M	L	F	W	B	Sources
Perennial grasses cultivated solely for bioenergy	Cropland or degraded land	Low N input	+	+	+/-/n.e.	+	+	Davis et al. (2013), Immerzeel et al. (2014), Kalt et al. (2020), Richards et al. (2017), Rowe et al. (2011), Whitaker et al. (2018)
Perennial grasses cultivated solely for bioenergy	Primary forest	Low N input	-	-	+/-/n.e.	-	-/+	Richards et al. (2017), Davis et al. (2013), Immerzeel et al. (2014), Kalt et al. (2020)
Oil palm	Primary forest OR on peatland	High N input	-	-	+	-	-	Carlson et al. (2014), Fitzherbert et al. (2008)
Oil palm	Degraded former paper/pulp land on mineral soils	High N input	+/-	+		-	+	Azhar et al. (2015), Flynn et al. (2012), Wicke et al. (2008)
Corn	Corn with conventional tillage	No till	+	+	n.e.		n.e.	Davis et al. (2013), Qin et al. (2016), West and Post (2002)
Corn	Forest	Any	-	-	+		-	Davis et al. (2013), Qin et al. (2016), Immerzeel et al. (2014)
Short rotation woody crops	Cropland or degraded land	Wide spacing and harvested every 4 years	+	+	n.e./+	n.e./+	+	Busch (2012, 2017), Davis et al. (2013), Don et al. (2012), Landis et al. (2018), Robertson, Hamilton, et al. (2017), Rowe et al. (2009, 2011, 2013)
Short rotation woody crops	Primary forest	Any	-	-			-	Immerzeel et al. (2014)
Soy or canola	Cropland with continuous corn	In rotation with corn	+	+				Herridge et al. (2008), Tiemann et al. (2015)
Soy or canola	Forest	Any	-	-			-	Immerzeel et al., 2014
Sugarcane	Degraded pastureland	Low input	+	+		-		Oliveira et al. (2016), Taniwaki et al. (2017)
Sugarcane	Sugarcane	Switching from pre-harvest burning to green cane harvest	+	+				Davis et al. (2013)
Agricultural residue	Modest removal used for feed	Extensive removal		-		-		Anderson-Teixeira et al. (2009), Gregg and Izaurralde (2010), Kalt et al. (2020), Muth and Bryden (2013), Powlson et al. (2011)
Agricultural residue	Burning of residues	Modest removal	+			+		Portugal-Pereira et al. (2015)

Note: Mitigation effects only include changes in direct terrestrial GHG fluxes and exclude any emissions reductions associated with fossil fuel displacement as well as any changes in emissions due to indirect land use change. Additionally, the mitigation effect is relative to the specified prior land use, not necessarily to natural land.

Abbreviation: GHG, greenhouse gas.

2018). Increased extraction of biomass from existing forests to supply bioenergy can reduce forest carbon stock (Pingoud et al., 2018), while intensive forest management and expansion of forest area stimulated by bioenergy demand can increase forest carbon stock (Favero et al., 2020). For annual crops, management practices (tillage practices, crop residue management, the use of cover crops, manure applications and chemical fertilizer application rates) are important determinants of terrestrial GHG fluxes. Results vary between reviews, especially in relation to interactions with soil texture and climate (Bolinder et al., 2020). Some studies indicate that conversion to conservation tillage can shift maize from a GHG source to a net GHG sink (Davis et al., 2013; Qin et al., 2016; West & Post, 2002). While other studies note that the enhancement of soil carbon ascribed to conservation tillage has sometimes been over-estimated due to limited sampling depth (Baker et al., 2007; Olson & Al-Kaisi, 2015), recent meta-analyses have confirmed the benefit to soil carbon of zero tillage plus residue retention, especially in drier climates (Li, Li, et al., 2020; Sun et al., 2020). Importantly, management practices to increase soil carbon need to be continuously applied in order to contribute to an improved GHG budget as soil carbon sequestration is a reversible process (Andren & Katterer, 2001). Regardless of bioenergy feedstock type, if existing mature forests are converted to energy crops a reduction in terrestrial carbon stock is likely (Davis et al., 2013; Immerzeel et al., 2014; Richards et al., 2017).

3.1.2 | Land degradation

Planting biomass feedstocks on degraded land can reduce or reverse land degradation by improving soil fertility, increasing soil organic carbon and removing contaminants such as heavy metals (Don et al., 2012; Flynn et al., 2012; Robertson, Zhang, et al., 2017; Wicke et al., 2008; Witters et al., 2009). However, the specific effects depend on initial land conditions (Creutzig et al., 2015; Daioglou et al., 2017; Vaughan et al., 2018; Wicke et al., 2008), feedstock type and management practice (Davis et al., 2013). Integration of woody crops and perennial grasses with conventional annual crops can help enhance soil carbon sequestration, reduce soil erosion and mitigate dryland salinity (Busch, 2012, 2017; Landis et al., 2018; Rowe et al., 2009, 2011, 2013). Harvesting high proportions of agricultural and forest residues for bioenergy can have negative implications on soil fertility, erosion risk and soil carbon, as residues play a critical role in supporting the chemical, physical and biological fertility of soils (Anderson-Teixeira et al., 2009; Gregg & Izaurralde, 2010; Muth & Bryden, 2013; Powlson et al., 2011). Detrimental impacts can be mitigated by restricting residue extraction rates, compensatory measures (e.g. ash recycling, liming, fertilization) and/or changing the categories of residue extracted

or land type targeted for extraction (Cowie et al., 2006; Mouratiadou et al., 2020; Ranius et al., 2018).

3.1.3 | Food security

The effect of bioenergy production on food security depends predominantly on the scale/rate of deployment along with a variety of inter-linking contextual factors such as land tenure security and dependence on subsistence agriculture (see Section 3.2). In local contexts, industrial crops grown for bioenergy in low-income countries can reduce poverty and improve food security through stable income and capacity development, although measurement of food security outcomes is complicated by many inter-linking factors (Jarzebski et al., 2020; Mudombi et al., 2018). The use of food crops for bioenergy, or cultivation of energy crops on high-quality arable land can displace food production, leading to increased food prices and iLUC to meet demand for displaced food crops (Bento & Klotz, 2014; Condon et al., 2015; Persson, 2015; Smith et al., 2019; Tyner & Taheripour, 2008). The use of residues from agriculture or forestry, in contrast, generates additional income and minimizes competition for land, limiting the effects on food security (Smith et al., 2019).

3.1.4 | Water

Bioenergy production can have implications for water quality and availability; the sign and magnitude of the effect depend on geographic location, crop type, land management practice and the prior land use (Hamilton et al., 2015; Robertson, Hamilton, et al., 2017; Secchi et al., 2011; Thomas et al., 2009; Wang et al., 2017; Wu et al., 2012). Forests provide biomass together with other ecosystem services such as water purification and regulation of water flows in watersheds. Biomass extraction is compatible with maintaining high water quality in forested catchments, as long as sustainable forest management practices are followed (Neary, 2013). Re-/afforestation can have beneficial or detrimental effects on water availability, depending on scale and landscape position (Cao & Zhang, 2015; Ellison et al., 2012; Xiao & Xiao, 2018). When conventional crops are used as bioenergy feedstock, the impacts resemble those associated with cultivation for food. For example, oil palm usually receives very high levels of nitrogen fertilizer (Darras et al., 2019), leading to a risk of water pollution (Carlson et al., 2014). Fertilizer application rates for sugarcane vary by location; biological nitrogen fixation by endophytic bacteria has been found to reduce the need for fertilizer in Brazil (Boddey, 1995; Medeiros et al., 2006), but application rates in other countries can be high (Lisboa et al., 2011). When woody crops and perennial grasses replace, or are integrated with, conventional annual

crops, nitrogen eutrophication and water pollution can be reduced (Cacho et al., 2018; Davis et al., 2013; Larsen et al., 2017; Odgaard et al., 2019; Robertson, Zhang, et al., 2017).

3.1.5 | Biodiversity

The effect of bioenergy production on biodiversity depends on the feedstock, prior land use and where energy crops are placed in the landscape. Woody crops and perennial grasses can have co-benefits for biodiversity (Busch, 2012, 2017; Landis et al., 2018; Rowe et al., 2009, 2011, 2013) and many ecosystem services, especially when established in agricultural landscapes dominated by annual crop production where they can increase landscape heterogeneity and hence habitat diversity. However, replacing native grasslands and forests with energy crops has adverse impacts on biodiversity (Fitzherbert et al., 2008; Immerzeel et al., 2014).

As bioenergy systems are commonly associated with agriculture and forestry systems that produce multiple products, biodiversity impacts also arise indirectly from the way agriculture and forestry is affected by bioenergy implementation. For example, Di Fulvio et al. (2019) determined that supplying biomass for energy in the EU through a combination of sustainably managed forests and perennial energy crops is likely to be less detrimental to global biodiversity than utilizing conventional food and feed crops as bioenergy feedstock. But, as the same authors show, the indirect biodiversity impacts caused by displaced food production in the EU, remains a driver of global biodiversity loss through iLUC.

3.2 | Implications of the scale and pace of deployment

There are contrasting viewpoints concerning the possible, or desirable, scale for bioenergy in general and energy crops in particular. On the one hand, there are concerns that the bioenergy sector will compete for biomass and land, and that expansion to significant scale will increase the pressure on remaining natural ecosystems as well as water resources (Bailey, 2013; Bárcena et al., 2014; Bonsch et al., 2015; Chang et al., 2016; Haberl et al., 2013; Pahl-Wostl, 2017; Rulli et al., 2016; Smith et al., 2016). This concern is substantiated by the well-documented impacts of historical forest conversion and cropland expansion (IPBES, 2019; IPCC, 2019b). In addition, numerous modelling studies have quantified the potential consequences of large scale bioenergy deployment on food security (Hasegawa et al., 2020; Humpenöder et al., 2018; Hurlbert et al., 2019; Popp et al., 2017; Smith et al., 2019) as well as water scarcity (Bonsch et al., 2015; Heck et al., 2018; Hejazi et al., 2014;

Humpenöder et al., 2018; Smith et al., 2019) and biodiversity (Heck et al., 2018; Hurlbert et al., 2019; Smith et al., 2019).

Global modelling studies show that large-scale deployment of energy crops is associated with trade-offs and risks for adverse side effects, where the extent of negative consequences depends on the socioeconomic context (Hurlbert et al., 2019) and specific land use scenario. For example, Humpenöder et al. (2018) showed limited effects on sustainability with 6.7 million km² of bioenergy plantations in scenarios with low population and less resource-intensive food demand. In a similar scenario, Heck et al. (2018) found significant pressure on land and water resources if the area with monoculture plantations providing biomass solely for bioenergy exceeded 8.7 million km². There can also be food security impacts due to increasing food prices if food and feed crops are diverted to biofuel production, or lands previously used for food crops are used for energy crops (Bailey, 2013; Franz et al., 2017; Kline et al., 2017; Mbow et al., 2019; Pahl-Wostl, 2017; Popp et al., 2014; Rulli et al., 2016; Schröder et al., 2018; Yamagata et al., 2018).

On the other hand, increased bioenergy demand can also support increased food production and lower prices in the longer term, as higher commodity prices and market stability can increase agriculture investment (Kline et al., 2017; Rosillo-Calle, 2016). Changes in food consumption patterns towards food options with lower land requirements (Clark et al., 2020; Parodi et al., 2018; Rosenzweig et al., 2020; Springmann et al., 2018; van Vuuren et al., 2018) can help reduce the pressure on land resources in a scenario where biomass use for energy increases.

There are many examples showing how the agriculture and forestry sectors can devise management approaches that enable biomass production and use for energy in conjunction with supply of food, construction timber and other bio-based products, while avoiding further conversion of natural ecosystems. Principal means include changes in agriculture practices to increase cropping intensities and yields and improve livestock productivity (Andrade et al., 2017; Brinkman et al., 2021; Cassman & Grassini, 2020; de Souza et al., 2019; Gerssen-Gondelach et al., 2017; Ramírez-Contreras et al., 2021), forest management practices enabling biomass harvest for energy (Dale et al., 2017; Ghaffariyan et al., 2017; Spinelli, 2019), and changes to industrial processes to improve biomass conversion efficiencies and use residues and waste to meet internal process energy needs and produce fuels, electricity and heat for use outside the industry (Hagman et al., 2018; Isaksson et al., 2012; Negri et al., 2020; Pettersson & Harvey, 2012). Furthermore, new biomass production systems can be integrated with existing agriculture and forestry systems (incl. marginal/degraded lands) so as to enhance biodiversity (Dauber & Miyake, 2016; Jager & Kreig, 2018) and ecosystem services (Asbjornsen et al., 2014; Berndes et al., 2008; Ferrarini et al., 2017). Examples of benefits include

reduced erosion and diffuse pollution (Christen & Dalgaard, 2013; Livingstone et al., 2021; Ssegane & Negri, 2016; Ssegane et al., 2015; Styles et al., 2016; Zumpf et al., 2017), flood regulation (Englund et al., 2020; Garg et al., 2011), pest and disease control (Bianchi et al., 2006; Holland et al., 2015; Meehan et al., 2012; Werling et al., 2014), phytoremediation (Berndes et al., 2004; Zalesny et al., 2019) and soil carbon sequestration improving soil productivity (see Section 3.1). As further discussed in Section 4, governance measures are needed to resolve some of the barriers to deployment of this type of multifunctional biomass production systems.

The targeting of marginal and degraded land is a commonly proposed strategy for reducing land use competition and pressure on natural ecosystems (Woods et al., 2015). Further, the cultivation of suitable energy crops on degraded or abandoned agricultural land of marginal profitability for agriculture can help restore soils and enable later food crop production (Fritsche et al., 2017). However, biomass production on marginal lands may require economic support due to relatively higher input requirements and lower yields (Dimitriou et al., 2011). The potential for bioenergy production on marginal/degraded lands is uncertain. Estimates of area of marginal and degraded land range from 5 to 60 Mkm² (Cai et al., 2011; Gibbs & Salmon, 2015; Woods et al., 2015), and the definition of 'marginal', the accuracy of land classification and the status as 'unused' are contested (Ariza-Montobbio et al., 2010; Fuss et al., 2018). For example, high resolution crowd-sourced assessment of imagery to exclude utilized land produced a range of 0.56–10 Mkm² (Fritz et al., 2013). Further, abandoned agricultural land of marginal profitability for cropping can have high biodiversity values.

The pace of expansion is also important to consider when assessing impacts of bioenergy expansion. As for many other mitigation options, the scenarios resulting from IAMs show very rapid technological and societal uptake of bioenergy, compared with historical trends (Brown et al., 2019; Turner et al., 2018; Vaughan & Gough, 2016). Theoretical analyses (Alexander et al., 2013) and real-world experiences (Brown et al., 2018; Dimitriou et al., 2011) indicate that it can be challenging to ramp up biomass supply at the rates found in modelling studies. Many of the time lags associated with the uptake of bioenergy cropping (Brown et al., 2019) relate to the role of land user behaviour in underpinning land use decision-making (Alexander et al., 2013). Behavioural processes and other institutional aspects are rarely included in land use models and IAMs (Brown et al., 2017) and hence these models and scenarios may overestimate the possible rate of bioenergy deployment (Brown et al., 2019). In addition, such rapid expansion of bioenergy production could have implications for international supply chains, logistics and the risk of GHG emission leakage (Daioglou, Muratori, et al., 2020; Junginger et al., 2019). Moreover, bioenergy provision under politically unstable and/or weak governance conditions

may also be a problem (Englund & Berndes, 2016; Erb et al., 2012; Searle & Malins, 2014).

If the level of bioenergy supply increases rapidly, there is likely higher conversion pressure on natural ecosystems where climatic and edaphic conditions suit energy crops, especially if food production is favoured on existing agriculture lands. Aside from biodiversity losses (Behrman et al., 2015; Hof et al., 2018), GHG emissions caused by land conversion can then diminish the climate benefits of bioenergy, especially if high carbon stock land (e.g. dense forests and peatlands) is converted (Behrman et al., 2015; Harper et al., 2018; Harris et al., 2015; Popp et al., 2011; Valdez et al., 2017).

Given the uncertainties in the area of unused and degraded land and the future requirement of land for food production, the current lack of comprehensive global studies that investigate the potential to integrate biomass production with agriculture and forestry, and other factors, it is not possible to quantify the amount of biomass that can be produced sustainably.

3.3 | Implications of land use change

Energy crops can be established through conversion from one land use category to another, such as from forest or grassland to annual crops such as soy. This direct land use change (dLUC) occurs where the energy crop is established. iLUC occurs elsewhere as a consequence of the dLUC and market mediated impacts. For example, if agricultural land is diverted to energy crops, deforestation may occur elsewhere to replace the former agricultural production (Egeskog et al., 2016; Fuchs et al., 2020). Land area impacted by iLUC can be minimized when biomass is obtained from crop and forest residues or from energy crops grown on unused land.

Where there is a change in land use to establish a bioenergy crop, dLUC effects can be quantified and attributed to a biomass producer using methods for assessment of carbon stock change in biomass and soil, such as on-ground measurement (stem diameter, soil sampling), earth observation techniques and modelling (e.g. FAO, 2019; GFOI, 2016; IPCC 2019c; Smith et al., 2020). Attribution is more challenging for iLUC because, by definition, it is not directly connected to a biomass producer, and there are many interacting drivers of land use change (Efroymsen et al., 2016; Egeskog et al., 2016). Instead iLUC effects need to be quantified using modelling approaches, such as general equilibrium models, that consider second order factors such as prices, government policy, regulations, trade relationships and market expectations (Chen et al., 2021; Di Lucia et al., 2012, 2019; Hudiburg et al., 2016; Khanna & Crago, 2012; Khanna et al., 2017; Malins et al., 2014; Wicke et al., 2012). Global IAM modelling frameworks capture the land use/land cover and GHG impacts of iLUC, but only at a highly aggregate regional level.

Indirect land use change emissions are most significant for liquid biofuels from crop-based feedstocks such as maize, wheat and soy (Ahlgren & Di Lucia, 2014; Chum et al., 2011; Valin et al., 2015; Wicke et al., 2012). Median iLUC estimates for biodiesel (52 g CO₂e/MJ) and bioethanol (21 g CO₂e/MJ; Woltjer et al., 2017) are on the same scale as the potential savings from displacing fossil gasoline and diesel (~90 g CO₂/MJ; Malins et al., 2014). However, there is significant variation across feedstock; for example, median iLUC estimates for palm biodiesel are much higher (216 g CO₂e/MJ) than other feedstocks (Woltjer et al., 2017). A limited number of studies calculate iLUC values for lignocellulosic crops; median iLUC estimates are lower (5 g CO₂e/MJ) as most of the studies assume that the land would be otherwise unused for food or feed production (Woltjer et al., 2017).

Variation between iLUC estimates is considerable and can be attributed to differences in modelling approaches, input data, parameterization, scenario assumptions and spatial coverage (Ahlgren & Di Lucia, 2014; Rajagopal & Plevin, 2013; Woltjer et al., 2017). Estimates of iLUC effects are also non-linear and will change with the level of biofuel demand and land conversion (Melillo et al., 2009). A single biofuel project, for instance, may have negligible iLUC emissions when assessed in isolation (Di Lucia et al., 2019), and in cases where bioenergy policies induce the conversion of pasture or marginal land to forestland carbon stocks may be increased (Dale et al., 2017; Duden et al., 2017).

While there is high level of confidence that the LUC impacts are critically important in determining the contribution that biomass can make to global mitigation pathways, the practicality, validity and effectiveness of iLUC GHG estimates for policy making remain highly contested (Di Lucia et al., 2021; Efroymsen et al., 2016; Egeskog et al., 2016; Finkbeiner, 2014; Khanna et al., 2017; Mai-Moulin et al., 2021). As improvements in iLUC quantification methods failed to reduce uncertainty and increase reliability of iLUC factors, it is not possible to determine the actual iLUC resulting from biomass production with confidence, and approaches that integrate bioenergy policies and land protection measures, covering all land-use related products, are suggested as more effective policy options to prevent indirect effects (Daioglou, Woltjer, et al., 2020; Sumfleth et al., 2020; see Section 4.4).

4 | POLICIES, INSTITUTIONS AND GOVERNANCE

It is beyond the scope of this paper to review all relevant bioenergy policies, institutions and governance mechanisms. Thus, we focus on broader governance approaches that have had—or may have in the future—significant influence on bioenergy deployment for climate change mitigation. Reflecting

on overall frameworks as well as empirical evidence on bioenergy implementation can help to qualify the interpretation of bioenergy mitigation potentials and scenarios. We first discuss the need for common metrics and transparent accounting systems to support effective implementation of policies and governance mechanisms. We provide an overview on governance issues and more detail on the three key aims of bioenergy governance: expanding markets and technology deployment, ensuring sustainability and addressing the impacts of competition for biomass and resources (including cross-sectoral approaches). Legislation, agreements or regulations might address some or all of these aims across multiple resource management domains, due to the multi-sectoral and multi-level nature of bioenergy markets and impacts.

4.1 | Measurement and accounting for biomass impacts

The IPCC publishes guidance (most recently, IPCC, 2019c) used by parties to the United Nations Framework Convention on Climate Change (UNFCCC), to prepare comprehensive national GHG inventories, divided by sector. One of the complications in assessing the total GHG flux associated with bioenergy under UNFCCC reporting protocols is that fluxes from different aspects of the bioenergy life cycle are reported in different sectors and their attribution to bioenergy is not apparent. While non-CO₂ GHG emissions (CH₄, N₂O) from bioenergy are reported in the energy sector, CO₂ emissions from bioenergy are not counted in that sector because changes in carbon stocks due to biomass harvest or land-use change related to bioenergy are already reported in the agriculture, forestry and other land-use sector at the time of harvest. Emissions from use of fertilizers are captured in the agriculture sector, while fluxes related to transport of farm inputs, biomass and energy products, electricity and fuel use in conversion to energy products, and removals due to CCS are reported in the energy sector. IAMs follow a similar reporting convention. Thus, the whole life cycle GHG effects of bioenergy systems are not readily isolated within national GHG inventories, modelled emissions estimates or databases containing modelled emissions estimates (e.g. Huppmann et al., 2018; see also Haberl, 2013; IPCC, 2006; Rogelj et al., 2018). The picture is further obscured by the accounting rules used to track compliance toward climate targets. For example, in the second commitment period of the Kyoto Protocol, a policy-driven increase in harvest, such as for bioenergy, could be included in the 'forest management reference level', enabling bioenergy-related emissions to be excluded from accounting (Grassi et al., 2018). This cross-sectoral and diverse nature of reporting and accounting tends to complicate identification of the effects of increased biomass use for bioenergy. This identification is also hampered because data on

bioenergy can be surprisingly patchy, outdated or inaccessible. For example, a well-documented 20% gap in statistics between reported wood sources and uses at EU level is mostly due to underreporting of wood use for energy (Camia et al., 2020).

These challenges in GHG reporting and accounting for bioenergy can affect the credibility of bioenergy in mitigation scenarios (e.g. Norton et al., 2019; Searchinger et al., 2018), which in turn impacts the political and regulatory environment and the opportunities and constraints in bioenergy markets. Climate and environmental policy decision-makers tend to resort to regulatory instruments rather than financial or economic instruments when faced with deep uncertainties (Bellamy, 2018; Torvanger, 2018). In addition to that the climate change mitigation potential of bioenergy is highly context dependent, results from assessments of the climate change effects of bioenergy are highly dependent on the choice of baselines (counterfactual), system boundary, spatial scale and timeframes (Cherubini et al., 2009; Cintas et al., 2017; Koponen et al., 2018), adding further uncertainties; different policy aims or context (e.g. planning, monitoring, long-term strategies) require different accounting approaches and methodology choices (Buchholz et al., 2014). Ensuring transparency, consistency and credibility in comparison between bioenergy systems, and with other mitigation options, is therefore a substantial challenge. The significance of bioenergy in climate mitigation scenarios means that decision-making under such uncertainties requires an ongoing co-evolution between bioenergy markets and governance approaches (Slade et al., 2018).

4.2 | Implications of bioenergy governance

The institutional context for modern bioenergy has evolved during recent decades as bioenergy markets and technologies transitioned from a concentration in a few countries (e.g. Brazil, Sweden, USA) to more regional and globalized patterns of deployment and implementation (Hultman et al., 2012; Silveira & Johnson, 2016). Biofuels and bioenergy have been promoted not only for climate change mitigation but also for energy security and rural development (Araújo et al., 2017; Souza et al., 2017). A variety of policy instruments such as biofuel mandates, heat/power feed-in tariffs and production subsidies have been introduced to stimulate new applications and markets (van Meijl et al., 2015; Su et al., 2015).

Good governance espouses principles such as transparency, fairness, effectiveness and inclusiveness (Devaney et al., 2017). Bioenergy governance can be public, private or mixed, and may span different levels from local to global in addressing some or all elements of biomass demand and bioenergy supply chains. Bioenergy is more complex than other

energy sources in that it encompasses all energy carriers and end-use sectors, while the supply of biomass cuts across different land and resource uses (e.g. agriculture, forestry, livestock), which generally have existing governance mechanisms. Consequently, governance of biomass and bioenergy markets presents a greater variety of inter-linkages and complexities compared to other energy sources, which can in turn result in additional conflicts or synergies. Both the legal framework and the capacity for enforcement must be considered (Englund & Berndes, 2016). Weak governance and/or poor institutional capacity may lead to under-exploitation of biomass resources where they might otherwise offer sustainable and cost-effective solutions, but in other circumstances might lead to over-exploitation that affects local livelihoods and/or ecosystem health (Johnson et al., 2020). The limited extent to which governance systems can be effectively represented in IAMs, or given as a constraint to IAM scenarios, exacerbates the difficulty in quantifying the amount of biomass that can be produced sustainably.

Governance of global trade has a significant influence on the impacts of bioenergy on climate and biodiversity. As pointed out by Fuchs et al. (2020) in commenting on the European Union's (EU) Green Deal, domestic climate targets and other green policies may result in increased climate impacts and biodiversity loss in other countries unless the principles for international cooperation and governance of global trade in products reflect and disincentivize their environmental and social externalities. Options include, for example, ensuring the implementation of robust sustainability criteria for imported bioenergy, or carbon border adjustment mechanisms (such as the one currently being considered in the EU) extended to account also for the biodiversity and climate profiles of imported products.

4.3 | Expanding markets and technology deployment

Although the scope of the paper precludes a detailed discussion on bioenergy policies, a brief overview is provided here to note the variety of policies that have—or can—encourage expansion in bioenergy market volume (scale) as well as the diversity of applications and products, including platforms that widen the scope through multiple products and multi-functional landscapes (Baumber, 2017; Scarlat et al., 2015). The approaches require coordination with the different sectors and energy carriers (e.g. heat, electricity, liquid fuels) across which bioenergy competes, with other renewables as well as with different bioenergy applications drawing on a common biomass resource base (Pischke et al., 2019; Tosun & Leininger, 2017). Social and political constraints to BECCS suggest that it will require much stronger regulatory frameworks in order to scale up (Fridahl & Lehtveer, 2018).

Effectiveness of these policy options relates to how well they are targeted, whether they have significant trade-offs and/or co-benefits with other objectives and whether international trade or transnational impacts are involved (Webster, 2020). Impacts that are readily managed at smaller scales may require quite different governance approaches for biomass, land and water use at the large scales and rapid deployment required to contribute significantly to climate stabilization objectives (Souza et al., 2017; Stenzel et al., 2019). Due to the linkages and interactions between biomass uses and applications, coordination is required as markets grow, posing risks when done poorly but considerable opportunities when done well (Purkus et al., 2017). Strengthening institutions and governance approaches through regional and pan-national learning and international cooperation platforms (such as the Global Bioenergy Partnership¹ and BioFuture Platform²) is valuable due to the diversity of applications and systems.

4.4 | Ensuring Sustainability

A variety of mechanisms have been used to promote more sustainable bioenergy applications and investments, including regulatory and financial instruments, standards and certification systems. Dozens of sustainability certification schemes were established already a decade ago after the EU and other countries/regions established incentives promoting biofuels and bioenergy (Scarlat & Dallemand, 2011). These schemes rely on particular metrics and impact categories, whereas the integration of bioenergy plans with ecosystem service provision can offer a complementary approach to sustainability associated with governance at the landscape level rather than governance for markets or technological systems (Dale et al., 2010, 2016). A current example, the new Common Agriculture Policy in the EU introduces so-called 'Eco-schemes' where farmers can receive direct payments for implementing practices beneficial for climate, water, soil, air and biodiversity (European Commission, 2019). Such schemes may serve to compensate farmers for enhanced ecosystem services and other environmental benefits provided by multifunctional biomass production systems previously described (Section 3.2).

Sustainability indicators and schemes have evolved over time, extending into a variety of social, technical, environmental and economic domains. Generally, technoeconomic impacts are reported as positive, whereas socioenvironmental impacts are reviewed as potentially negative (Robledo-Abad et al., 2017). As bioenergy systems become better integrated

with other uses of biomass and bio-based products, sustainability will increasingly need to be assessed in a broader bioeconomy perspective (Lewandowski, 2015; Moosmann et al., 2020). Governance of the broader bioeconomy at the international level remains limited although interest is growing for regional cooperation in established economic blocs (e.g. EU, Eastern Africa) where common infrastructure and complementarity offer advantages over national-centred bioeconomy strategies (Bößner et al., 2021). With increasing international cooperation and trade in bioenergy, some aspects of governance are transnational and also require greater collaboration between public and private sectors (Ponte & Daugbjerg, 2015).

4.5 | Addressing competition for biomass and resources

There is concern that expansion of bioenergy will cause competition for biomass, land, water and other resources and may affect the quantity or location of food production (Ben Fradj et al., 2016; Humpeöder et al., 2014). While competition can stimulate improvements in productivity and economic efficiency in market-based systems, concerns arise due over impacts on vulnerable people and ecosystems, and food security. However, food security and food production are rather different issues; reconciling bioenergy expansion with food security in developing countries requires greater stakeholder engagement, investment in rural extension, and promoting stable markets that incentivise local production (Kline et al., 2017). Among the major end-use categories (food, feed, fuel/energy, fibre and materials) for all the terrestrial biomass that is extracted and used globally, feed (for animals) accounts for the majority (Piotrowski et al., 2015); thus, potential competition for land and biomass due to bioenergy is more closely connected in global terms to demand for animal feed crops rather than agricultural crops used for direct human consumption (Muscat et al., 2019; Tomei & Helliwell, 2016). Changes in diet therefore offer considerable savings in land, biomass and GHG emissions, thereby also freeing up land and biomass for other uses (Smith et al., 2019). Pasture lands account for a significant share of lands that could be targeted for bioenergy. The net effect on land carbon storage of converting pasture lands to bioenergy plantations depends on historic pastureland management, which determines soil carbon storage in pastures, and type of bioenergy plantation established, which determines carbon storage in soil and vegetation after the conversion (Cowie et al., 2006; Davis et al., 2013). Bioenergy potential studies could consider a broader range of sustainable intensification options and multifunctional landscape approaches, which can have significant implications for how sustainability constraints are applied (Kluts et al., 2017). Incorporating bioenergy into landscape

¹<http://www.globalbioenergy.org/>

²<http://www.biofutureplatform.org/>

design can reduce conflicts and improve co-benefits but requires good governance in the form of inclusive stakeholder approaches, upfront planning and clear communication on aims and concerns (Dale et al., 2016). Especially in the global South, combining bioenergy production with agroforestry and other agroecology approaches offers a number of useful synergies between climate, food security, energy access and rural development objectives; implementation requires strengthened institutional capacity in rural areas, policy coherence efforts and improved land tenure (Sharma et al., 2016).

5 | DISCUSSION AND CONCLUSIONS

Mitigation pathways such as those assessed in the IPCC SR1.5 and SRCCL reports rely heavily on the deployment of bioenergy and BECCS. Bioenergy plays a key role in decarbonization in modelled future pathways, supporting energy system transformation, especially in hard-to-abate applications such as aviation and shipping, and, when linked with carbon capture and storage (BECCS), can provide CDR. Most of the mitigation pathways presented in the IPCC SR1.5 and SRCCL reports were designed with mitigation as the only target. Such assessments find that restricting the use of bioenergy and BECCS can increase the cost of mitigation. However, these analyses neglect both positive and negative implications of bioenergy and BECCS on other sustainability criteria, which could alter bioenergy deployment. Additionally, many elements of bioenergy supply and feasibility are missing from IAMs, including some feedstocks, management practices and aspects of governance. Representation of land suitability/quality is limited. How a refined representation of land quality and bioenergy systems in IAMs would affect the deployment of bioenergy or other mitigation options in mitigation pathways is unknown. Some improvements (e.g. the addition of integrated biomass systems and forest management) may result in increased bioenergy production, while others (e.g. reserving more land for nature protection to reflect higher ambitions concerning conservation) will very likely result in decreased bioenergy production.

The implications of bioenergy supply on mitigation and other sustainability criteria are context dependent and influenced by feedstock, management regime, climatic region, scale of deployment and the counterfactual land use and energy system, as well as the time frame and spatial scale considered. Every feedstock assessed could result in positive effects on sustainability or in negative effects, depending on the criteria chosen, as well as the local context, management regime, prior land use, and scale. For example, the use of agricultural and forestry residues does not require dedicated land, reducing the risk for land competition and associated

negative implications on food security; however, excessive removal of residues could result in land degradation. Dedicated bioenergy crops, for example, perennial grasses and woody crops, could adversely impact food security if planting these crops results in reductions in food/feed production in a region, while densely planted woody crops can lower groundwater levels and cause downstream water scarcity in dryland regions. However, integration of suitable perennial biomass production systems in regions dominated by annual crop cultivation has been shown to have positive benefits across a range of sustainability criteria, including soil health, biodiversity and water quality. Such integration can, in some instances, help maintain or increase food and feed production in a region.

Given the limitations of the existing models, and uncertainty over the future context with respect to the many variables that influence availability of biomass and land resources, it is not possible to precisely quantify the sustainability implications for different scales of bioenergy implementation. It is not possible to determine the scale of bioenergy use at which any detrimental impacts outweigh the mitigation and other benefits, due to uncertainties in the amount of mitigation, uncertainties in the consequences of bioenergy at different scales, uncertainties in the effectiveness of governance, and uncertainties in how to compare or aggregate across different sustainability dimensions. Ultimately, the scale of bioenergy implementation depends on the priority given to bioenergy products versus other products obtained from the land—food, paper, bioplastics and other bio-based products—and on attainable total biomass production in agriculture and forestry. This in turn depends on natural conditions, land use practices, and on how societies understand and prioritize nature conservation and protection of land and water resources.

The dependence on large-scale deployment of bioenergy in mitigation scenarios carries risks. Many mitigation pathways delay stringent cuts in emissions until the second half of the 21st century, relying on negative emissions achieved through deployment of BECCS to compensate. Rapid and large-scale deployment of monoculture biomass plantations (at the higher end of what is found in pathways meeting the 1.5 or 2°C goal) will likely have adverse side effects for one or more sustainability criteria (e.g. food security, water resources, biodiversity, etc.). In addition, continued climate change in the decades prior to BECCS deployment has implications for bioenergy potential and terrestrial carbon storage.

The use of bioenergy in a mitigation portfolio, while minimizing adverse impacts on sustainability, requires integrative policies, coordinated institutions and improved governance mechanisms. Even at small scales, bioenergy can have negative implications for sustainability in some contexts. The fact that bioenergy operates across multiple energy carriers, sectors and applications presents additional governance

challenges especially in countries with weak institutions and poor infrastructure. At the same time, it also creates opportunities for synergies in making simultaneous improvements across multiple sectors and/or markets. The heterogeneity of bioenergy systems and markets calls for quantitative modelling to be complemented with a broad stakeholder dialogue that can illuminate alternative pathways for scaling up and scaling out. Additionally, the approach to using bioenergy in a mitigation portfolio will likely require adjustments as new knowledge is gained.

In conclusion, bioenergy and the use of land to produce biomass, is an important part of many climate mitigation strategies but there are limits (both known and unknown) to its use due to trade-offs with sustainability. At the same time, there are opportunities for win-win response options that can enhance mitigation, increase resilience and co-deliver across a range of sustainability criteria. Nevertheless, it is not possible to maintain current systems and trends in consumption patterns by simply replacing fossil carbon with biogenic carbon. Conservation and efficiency measures for energy, land and biomass can support greater flexibility in achieving climate change mitigation and adaptation. Further, wide deployment of technologies and systems that do not rely on carbon-based energy can constrain the biomass demand growth that will likely arise when countries seek to phase out fossil fuels while providing acceptable standard of living.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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