Bioenergy-induced land-use change emissions with sectorally fragmented policies

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Abstract

We assess the impact of different land-use emission policies within a broader climate policy framework on bioenergy production and associated land-use carbon emissions. We use the global Integrated Assessment Model REMIND-MAgPIE integrating the energy and land-use sectors and derive alternative climate change mitigation scenarios over the 21st century. If CO_2 emissions are regulated consistently across sectors, land-use change emissions of biofuels are limited to 12 $kgCO_2/GJ$. Without land-use emission regulations applied, bioenergy-induced emissions increase substantially and the emission factor per energy unit raises to levels slightly below diesel combustion (64 kg CO_2/GJ). Pricing these emissions on the level of bioenergy consumption diminishes bioenergy deployment and the associated CO_2 emissions, while failing to reduce the average emission factor. Despite effective reduction of land-use emissions, undifferentiated penalization of bioenergy use substantially increases mitigation costs. If supply side policies comprehensively regulate direct and indirect emissions, bioenergy can be produced much more sustainably.

Main

Introduction

To limit global mean temperature and to achieve the Paris climate targets, society needs to bring down global carbon emissions to net zero and strongly reduce non-CO_2 emissions[1]. Future cost-effective climate change mitigation strategies often rely on large-scale bioenergy deployment[2]. The use of biofuels provides a low carbon alternative to fossil fuel-based liquids as well as the possibility to enable carbon dioxide removal from the atmosphere using bioenergy with carbon capture and storage (BECCS)[3]. The combined ability of biofuels to overcome and compensate for decarbonization bottlenecks is a major driver of its future large-scale deployment[4–6]. However, the relevance of bioenergy as a means to climate change mitigation is also controversially discussed[7–9], since its production will be in competition with other land-use (LU) activities and thus increases the already existing pressure on land-systems[10,11]. For example, large-scale bioenergy production can threaten biosphere integrity and biogeochemical flows, might increase unsustainable freshwater use and may also lead to higher food prices[11–13]. Bioenergy also has substantially higher specific land requirements than other renewable energy sources[14]. There is thus a risk that the growing demand and willingness to pay for bioenergy induced by strengthened climate protection measures hits a land-use sector that is already under pressure today[12,15]. In addition, there is the threat that direct and indirect land-use change[16,17] (LUC/iLUC) CO_2 emissions associated with bioenergy production can largely offset abated emissions[18,19].

A broad range of studies has investigated LUC and iLUC emissions induced by bioenergy production at different locations. They have identified vastly different emission factors (EF) ranging from 0 to 100 kg $CO_2/GJ_{biofuel}$[20–23], which might be even higher than for oil derived diesel (74 kg CO_2/GJ[24]). This broad uncertainty reflects the heterogeneity of land types[23] – characterized by stored carbon content and crop yield rates – and the flexibility of land-use and initial land conditions[25,26]. Yet, these studies do not reflect the interplay between future global climate policies and the allocation of land areas for bioenergy and food production. Given that stringent climate policies are projected to be the main driver for bioenergy production[4], however, it is crucial to link the assessment of EFs to the future transformation pathways of the energy-system. Our study assesses bioenergy EFs under a range of alternative climate change mitigation policies and thereby closes this gap in the literature.

Most studies analyzing global climate change mitigation pathways using Integrated Assessment Models (IAM) consider, among others, the benchmark of an idealized climate policy framework putting a uniform carbon equivalent price on greenhouse gas (GHG) emissions from all sectors, sources and countries[9]. This is an effective policy to avoid carbon emissions from the land-use sector due to bioenergy production. However, in the current real-world situation, energy- and land-use policies are regionally and sectorally fragmented. While many countries already started to implement GHG emission pricing in the energy sector, institutional capacity building is much less developed in the agricultural and forestry sector[27]. The already high challenges in implementing carbon pricing in the energy system give an indication of the difficulties in pricing emissions from the land-use sector. Here additional technical and in particular governance challenges related to monitoring, reporting and verification (MRV) need to be overcome. It is also debated whether GHG prices should be the same in the energy and land-use sector, given differences in abatement cost curves and distributional impacts[28–30]. The implicit assumption in IAMs of institutional feasibility of LU mitigation has been criticized[31], since fragmented or even completely absent LU-based GHG regulatory schemes can lead to substantial emission leakage from regulated to unregulated regions[32,33] or sectors[18,34,35] involving excess bioenergy production, both factors counteracting mitigation efforts. Since LU-based regulatory schemes are hard to implement on a globally comprehensive level (i.e. on the supply side), there has been the proposal to regulate bioenergy consumption directly via import controls, volume caps or by attributing EFs to bioenergy – in particular biofuels (e.g. as part of EU directives[36]). While there have been studies analyzing auxiliary policy frameworks apart from a uniform carbon price[37,38], none of them systematically compared the effectiveness of LU-based regulator schemes, which may be weak or fragmented, with demand-side controls on bioenergy deployment in terms of EFs related to bioenergy production and its land-use displacement effects.

By comparing the effectiveness of different bioenergy demand- and supply-side policies to reduce the EF of bioenergy in climate change mitigation scenarios, we aim to answer the following research questions:

(1) If comprehensive LU-based regulation is not available, how effective can direct regulation of bioenergy deployment be in harnessing bioenergy while limiting its adverse impacts?

(2) To what extent would only weak and fragmented LU regulation be able to limit the adverse impacts of bioenergy deployment?

(3) How do different policy assumptions affect the level of carbon pricing necessary in the energy sector to achieve the Paris climate target?

Modeling Framework

We apply the IAM framework REMIND-MAgPIE[4,39,40] to derive climate change mitigation pathways that are compatible with limiting warming to 2°C by setting a carbon budget of 1000 Gt CO_2 to total energy- and LU-based CO_2 emissions from 2018 to 2100[41]. Key socio-economic assumptions on population, GDP, dietary choices and energy demand projections that drive the model results reflect a middle-of-the-road scenario (Shared Socioeconomic Pathway 2 (SSP2))[42]. The coupling of the energy-system model REMIND[43,44] with the LU model MAgPIE[45,46] allows for the analysis of feedback effects between bioenergy demand, production and associated LUC emissions. By comparing these pathways with a counterfactual scenario without bioenergy available for decarbonizing the energy sector, we extract the pure impact of bioenergy production on total and specific LUC emissions and on the mitigation strategies of the energy sector as well as on macro-economic costs. Specific emissions are thus calculated *ex-post* and we express the emission factor $EF_{ex\text{-}post}$ in terms of kg CO_2 emitted per GJ of biofuel produced.

Policy Design (detailed description in methods section)

While all scenarios reach the same climate target by imposing a uniform price on GHGs in the energy sector, they differ with respect to assumptions on bioenergy and LU-related policies (given in Table 1), implying different carbon price levels.

There are two benchmark policy assumptions, between which the different alternative approaches unfold. The scenario with a globally Uniform Carbon equivalent Price (***UCP***) in the energy- and LU sector marks the first best policy option to comply with the climate policy target reaching a carbon price of 147 \$/t CO_2 in 2050. This policy is contrasted with a scenario where the LU sector is lacking any regulatory scheme for controlling emissions (***noLUreg***), i.e. there is neither a price instrument on any type of land-use based GHG emissions nor any widespread land-protection scheme. The 2050 carbon price here reaches a much higher level of 291 \$/t CO_2.

As a first set of alternative supply-side policies we gradually explore the effect of different levels of fragmentation between energy- and LU sector. This is represented by reduced GHG price levels on LU sector-based emissions of 10-50% compared to the price on emissions from the energy sector (***LUprice10%-50%***). Alongside these price-based supply-side policies we explore the efficacy of various land-protection schemes, namely forest protection (***protForest, protPrimforest***), and the protection of distinct focus areas (***protBH***, ***protCPD***, ***protFF***, and ***protLW***).

Contrasted to supply-side policies that are difficult to implement at global scale, we examine how a demand-side tax on bioenergy consumption can reduce LUC emissions. We analyze the effect of different bioenergy tax levels, representing the uncertainty of potential bioenergy EFs (***bioTax10-50,*** c.f. Table 1 for a description of the tax levels). In addition, we explore scenarios, in which we impose a ban on bioenergy imports on top of the different bioenergy tax levels (***bioTaxNoImp10-50***), since a considerable amount of biomass can be consumed in regions other than the one where it is produced[47]. In particular, exports from tropical regions with high carbon stocks might promote additional LUC.

Scenario	Policy design
Benchmark policies	
UCP	Globally uniform* carbon price across energy- and land-use-sector
noLUreg	Globally uniform carbon price only within the energy sector; No regulation of land-use GHG emissions
Supply-side policies	
LUprice10-50%	Globally uniform carbon price within the energy sector; Globally uniform carbon price within the land-use sector at a level of 10-50% of the price in the energy system
protForest	Globally uniform carbon price only within the energy sector; Primary and secondary forests are protected
protPrimforest	Globally uniform carbon price only within the energy sector; Primary forests are protected
protBH	Globally uniform carbon price only within the energy sector; Biodiversity Hotspots are protected
protCPD	Globally uniform carbon price only within the energy sector; Centers of Plant Diversity are protected
protFF	Globally uniform carbon price only within the energy sector; Frontier Forests are protected
protLW	Globally uniform carbon price only within the energy sector; Last of the Wild areas are protected
Demand-side policies	
bioTax10-50	Globally uniform carbon price only within the energy sector; No regulation of land-use GHG emissions; Additionally bioenergy consumption is charged with a tax. The tax level is determined by the carbon price multiplied with a predefined, fixed factor given in $kgCO_2$ per GJ_{PE} of primary energy ("PE") dry matter biomass. E.g. bioTax20 stands for a policy charging bioenergy *as if* it had an EF of 20 $kgCO_2/GJ_{PE}$. Due to conversion losses 10-50 $kgCO_2/GJ_{PE}$ correspond to 24-122 $kgCO2/GJ_{biofuel}$ and while the tax level is expressed in units of primary energy, ex-post EFs are expressed in units of biofuel for a better comparability with other values from the literature.
bioTaxNoImp10-50	Globally uniform carbon price only within the energy sector; No regulation of land-use emissions; a Additionally a tax on bioenergy consumption of bioenergy as above; Bioenergy imports are prohibited

Table 1|Policy Design. *Scenarios are divided into the two benchmark scenarios (UCP and noLUreg), scenarios with supply-side policies (i.e. directly within the LU sector) and scenarios with demand-side policies (i.e. within the energy sector). *While carbon prices are globally uniform from 2050 on, they differ between regions before 2050 to some extend for reasons of interregional equity (see methods).*

Ex-post emission factors

In the absence of restrictions on land-use emissions (*noLUreg*) cumulative (2020 to 2100) bioenergy-induced LUC emissions increase more than ten-fold from 44 Gt CO_2 in the UCP case to 493 Gt CO_2 (Fig. 1a). This is qualitatively similar but quantitatively more muted compared with Wise et al.[18] Since global bioenergy production only doubles to 236 EJ/yr, $EF_{ex\text{-}post}$ on an 80 year time horizon increases from 12 kg $CO_2/GJ_{biofuel}$ to 64 kg $CO_2/GJ_{biofuel}$, which is only slightly smaller than the EF of diesel (Fig. 1b).

In between these benchmark scenarios supply-side and demand-side policies lead to different consequences for bioenergy and LUC emissions. While even a small fraction of the energy systems' carbon price level applied to terrestrial GHG emissions (*LUprice20%*) is sufficient to reduce $EF_{ex\text{-}post}$ to 33 kg $CO_2/GJ_{biofuel}$, a demand-side tax on bioenergy consumption is not affecting the specific average emissions attributed to a unit of bioenergy, since emissions only decline as a consequence of reduced demand. Interestingly prohibiting bioenergy imports is not effective at all, since the largest part of the biomass is consumed domestically in most regions and a trade moratorium reduces overall production and thus LUC emissions only to a small extend.

The impact of bioenergy on LUC emissions in the presence of land-protection schemes depends on the precise areas that are removed from the land-pool available for bioenergy production and other agricultural activities. While a policy protecting all forests resembles the *UCP* case to a large extend ($EF_{ex\text{-}post}$ = 24 $CO_2/GJ_{biofuel}$ and emissions of only 107 Gt CO_2 for *protForest*), removing only some focus areas from the available land-pool has only very limited effect on reducing bioenergy-induced LUC emissions and EFs from unregulated levels.

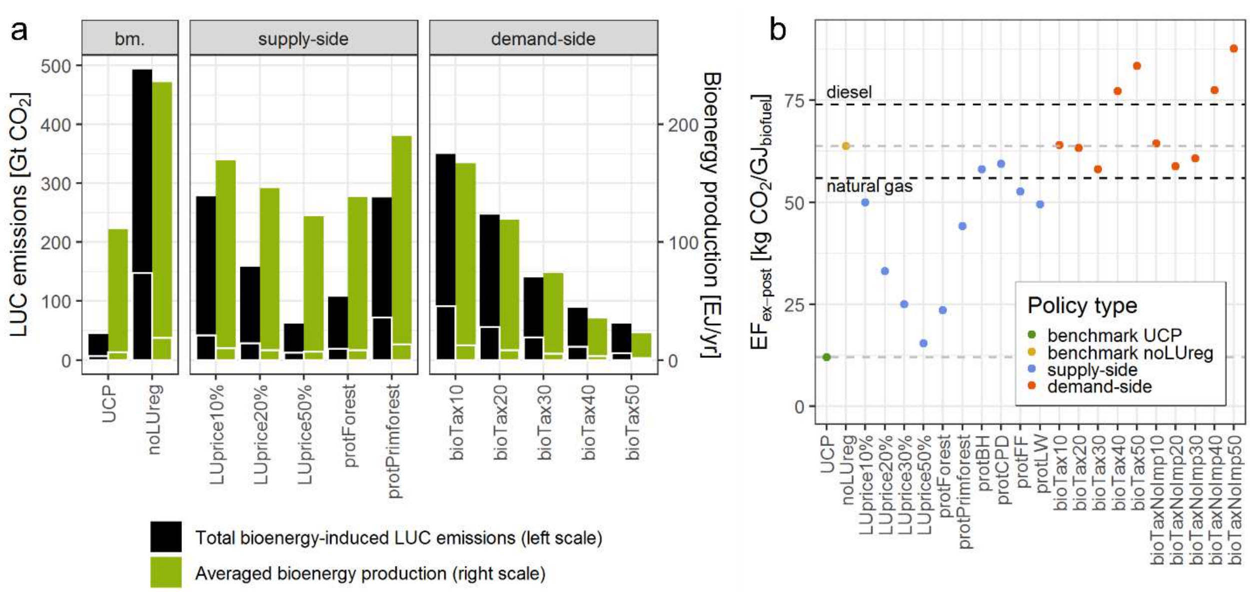

***Fig. 1| Bioenergy-induced LUC emissions, bioenergy production and emission factors.** (**a**) Emissions, given as the total global LUC emissions and bioenergy, given as the averaged annual global production, are both evaluated for period from 2020 to 2100 and shown for different policy settings. Besides the two benchmark scenarios ("bm."), policies are grouped into "supply-side" and "demand-side" policies. White bars indicate cummulative emissions in 2050 and the averaged annual bioenergy production until 2050, respectively. For reasons of clarity we only show a selection of policy settings, other scenarios are shown in Fig. S1 in the SI. (**b**) Ex-post EFs are given per unit of biofuel produced for different policy settings. Reference EFs for diesel and natural gas are taken from UBA[24]. For a comparison to EFs of N_2O see Fig. S4 in the SI.*

Spatial allocation of bioenergy production and emissions

Regarding the effect of distinct policies, we generally observe a considerable disconnect between the spatial patterns of bioenergy production and LUC emissions. We find that – irrespective of the policy design – a large fraction of LUC emissions does not originate from the land areas of bioenergy cultivation, but occurs *indirectly* at formerly forested areas or pasture, where agricultural activity displaced by bioenergy production is moved to (see Fig. 2). Those iLUC emissions as well as bioenergy plantations directly replacing carbon-rich ecosystems contribute to high emissions factors (as for example in the northern regions of South America for *noLUreg*, see Fig. 2 a,c,d). Without supply-side policies globally more than 85% of additional emissions induced by bioenergy production originate from territories that together only generate less than 16% of total biomass production (red and dark red wedges in Fig. 2 b). By contrast, the main part of the bioenergy (more than three quarters across all policy settings) is being produced with a direct emission factor of less than 37 kg $CO_2/GJ_{biofuel}$ (half the EF of diesel, blue wedges in Fig 2.), *directly* causing less than 10% of the total bioenergy-induced emissions if LU regulation policies are absent. Therefore, by only accounting for direct LUC emissions within major bioenergy producing regions, only a small fraction of attached emissions can be traced. Accordingly, the *total* iLUC emissions related to the *total* bioenergy production are considerable and vary strongly with the regulatory framework.

This leads to two conclusions. First, the high flexibility of the LU sector in reallocating agricultural uses makes iLUC emissions hard to avoid, although the absolute level depends on the underlying global LU regulatory framework. Second, previous studies analyzing the direct LUC EF of bioenergy often suggested that increasing bioenergy production is linked to increasing EF, implying that limiting bioenergy production can also effectively limit EF (e.g. Daioglou et al[23]). This rests on the assumption that expanding agricultural area due to bioenergy use proceeds along the lines of least marginal EF of land conversion. However, while such an allocation would be optimal from a sustainability perspective it is not the allocation that emerges in the land-use sector, as the EF is not the main criterion for allocating crop land by means of economic choices. As a consequence of this, a demand-side bioenergy tax reducing the overall consumption of energy crops does not automatically lead to sparing areas with high carbon stocks, as the allocation of emissions by EFs is not affected by the tax (compare *noLUreg* and *bioTax10*, Fig. 2 b).

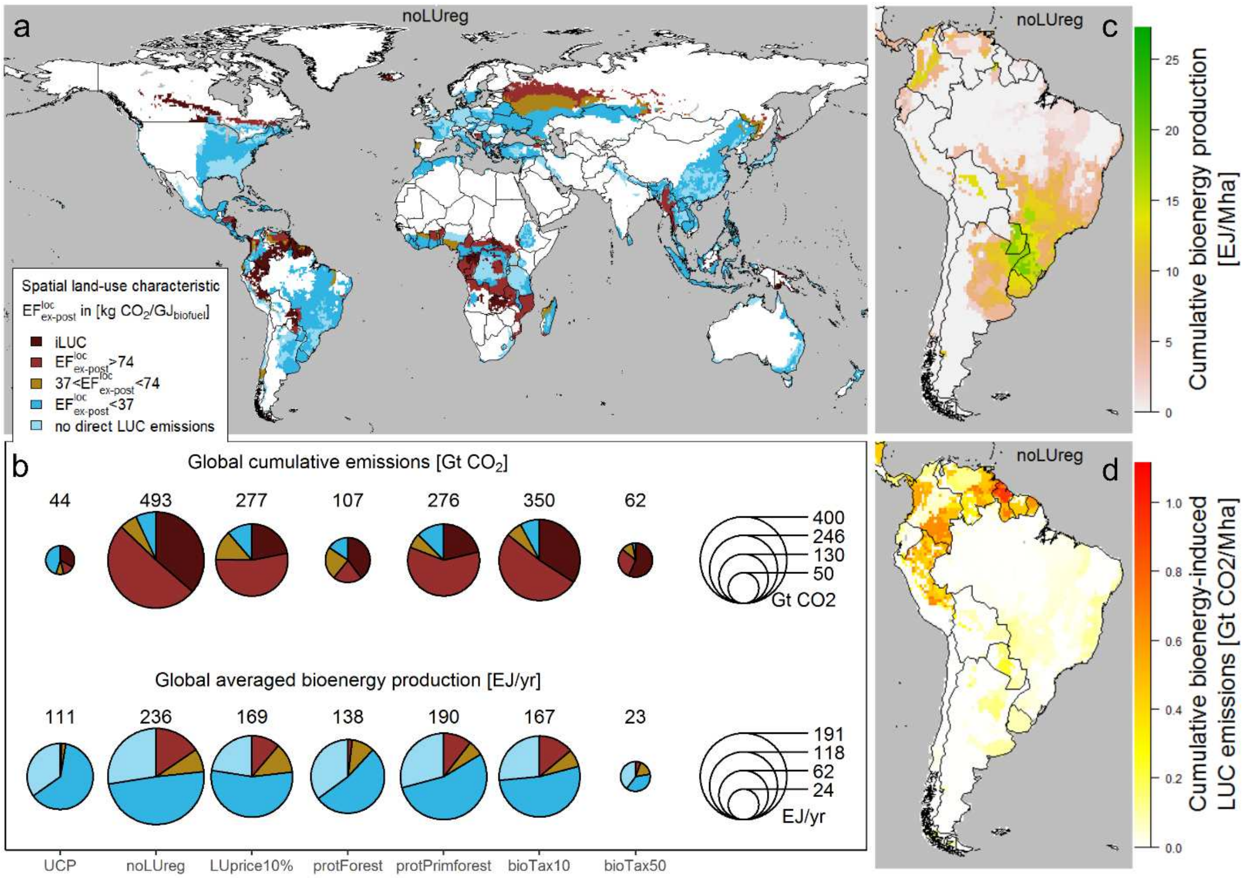

Fig. 2| Spatial allocation of LUC CO_2 emissions and bioenergy production. *Panel (**a**) shows a spatially disaggregated map of bioenergy EFs that emerge in the absence of LU regulation (noLUreg). There are territories, where bioenergy is being produced without additional LUC emissions at the place of production (bright blue areas). Here bioenergy is either being produced on marginal or abandoned land or on land, where it displaces other agricultural activities. On the other hand, natural vegetation can be converted to agricultural land to balance the production of agricultural goods that were displaced by bioenergy (dark red areas, iLUC emissions). Other territories are classified by $EF^{loc}_{ex\text{-}post}$, given by the ratio of bioenergy-induced emissions to bioenergy production (for reference, 74 kg CO_2/GJ is the EF of diesel[24]). In panel (**b**) the sizes of the pie charts reflect the total global bioenergy-induced LUC emissions and the global averaged annual bioenery production, respectively, for different policy assumptions (other scenarios are shown in Fig. S5, SI). The sizes of the wedges reflect the amount of emissions and bioenergy production and are color-coded according to the associated EFs as described in (**a**). Panels (**c**) and (**d**) show the spatial distribution of bioenergy production and bioenergy-induced emissions, respectively, for the example of South America. In all four panels quantities are cumulated over the period between 2020 and 2100. See methods section for a description of the analysis of $EF^{loc}_{ex\text{-}post}$ and the SI for figures of the other policy assumptions, including maps of baseline (not bioenergy-related) emissions.*

Components of CO_2 emissions and the role of BECCS

Regarding the composition of total cumulated CO_2 emissions, we observe vastly different allocations of the carbon budget for the varying policy assumptions. While cumulated emissions induced by bioenergy production up until 2100 will be offset by deploying carbon removal using BECCS and direct air capture with carbon storage (DACCS) technologies (Fig. 3a), in in the absence of comprehensive LU sector emission regulations a large fraction of BECCS removals will be offset by the additional LUC emissions (Fig. 3b). For instance, if regulations only comprise incomplete land protection schemes or a bioenergy demand-side tax, LUC emissions are relatively high in relation to the bioenergy production reflected by the high emission factor (44 to over 60 kg $CO_2/GJ_{biofuel}$). In such a regulatory framework, carbon removal by BECCS is largely used to offset these emissions. Hence, due to the heterogeneity and flexibility of the LU sector, incomplete regulation of the additional emissions caused by biomass production implies that bioenergy is not necessarily carbon negative, if combined with CCS (or at least only with a poor efficacy), but rather only carbon neutral. Without LU mitigation, only 15% of carbon dioxide removal from BECCS remain. Before 2050 cumulated bioenergy-induced LUC emissions even exceed BECCS savings by far for all policy settings except for a uniform carbon price (Fig. S6, SI). Note that this only compares LUC emissions with carbon removal, but does not account for fossil fuel substitution.

In comparison to the *UCP* policy, we furthermore observe that cumulated energy system emissions need to be reduced in scenarios with high LUC emissions to balance the total budget. The additional biomass is then used to accelerate the phase out of fossil fuels, particularly oil (Fig. S7, SI).

If bioenergy is priced on the demand-side in the range of LUC emissions caused on the supply-side, LUC emissions decrease with increasing tax level, but the reduced demand for bioenergy enforces a stronger and faster electrification in comparison to both the *UCP* and the *noLUreg* scenario (Fig. S8, SI). At the same time the share of emissions from the transport sector increases due to the lack of biofuels. The dwindling availability of biomass even leads to higher CO_2 prices (Fig. 3c) compared to the already high prices in *noLUreg*, which makes DACCS competitive as a means to compensate for residual emissions.

It is also worth noting that even a comparatively small carbon price on LU-sector-based emissions (*LUprice10%*) is sufficient to abate most of the non-bioenergy-related LUC CO_2 emissions (from 235 in *noLUreg* to 56 Gt CO_2). At the same time, the required carbon price is reduced by 35% from 291 to 193 $/t CO_2 in 2050 (Fig. 3c).

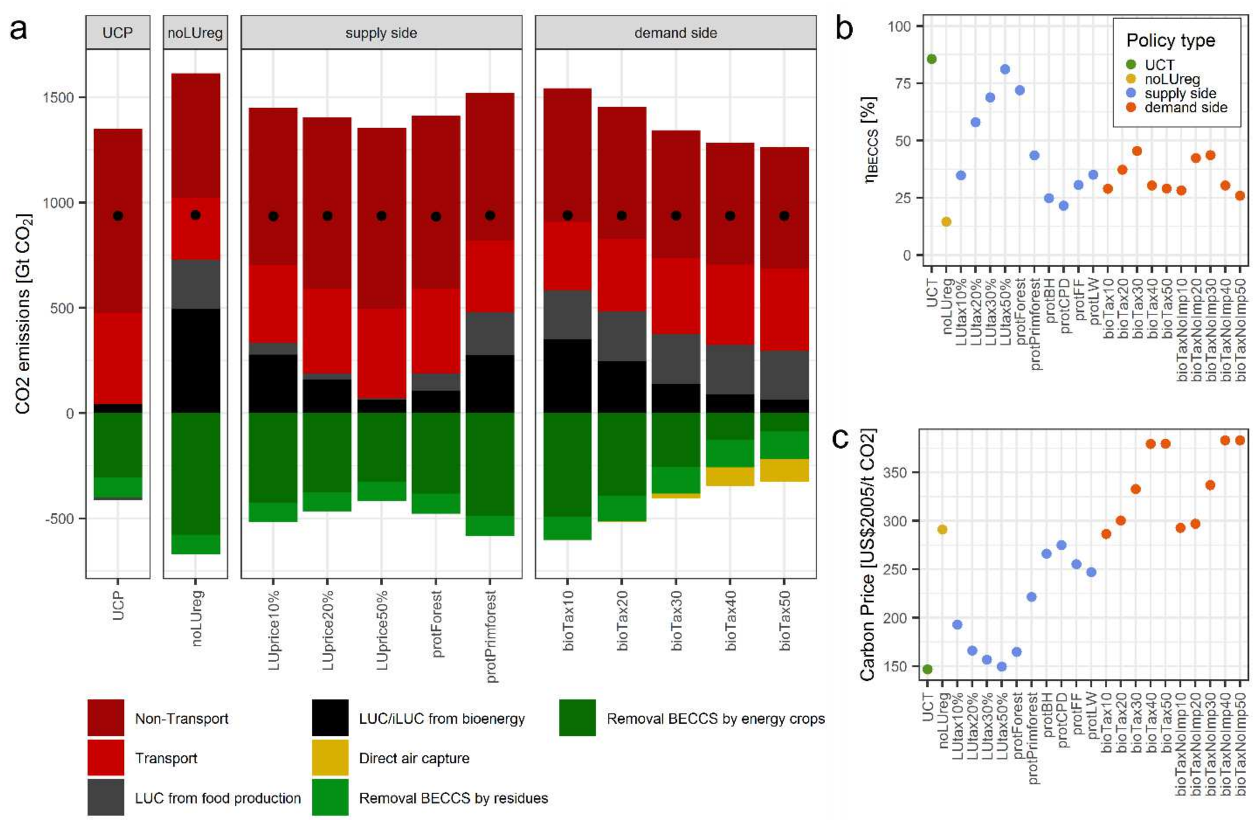

Fig. 3| Composition emissions, BECCS efficiency and carbon prices. (**a**) Composition of total anthropogenic CO_2 emissions, given for different policy assumptions cumulated from 2020 until 2100. Black dots refer to the net totals. LUC emissions not related to bioenergy production comprise CO_2 LUC emission from all other agricultural activities. Bioenergy from residues is assumed to be carbon neutral. For the calculation of the shares please refer to the methods section. Composition of the other scenarios are shown in Fig. S2, in the SI. (**b**) The BECCS efficiency factor η_{BECCS} is an indicator of how much of the sequestered carbon is virtually removed from the atmosphere if bioenergy-induced LUC emissions are subtracted. For instance, $\eta_{BECCS} = 15\%$ for noLUreg implies that only 15% of the CDR savings are effectively removed from the atmosphere, as the remaing 85% are offset by LUC emissions. (**c**) Shown are energy system GHG prices in the year 2050. After a phase in period, prices are equal across regions from 2050 on.*

Discussion and conclusion

In our study we analyzed the impact of bioenergy on LUC emissions in different climate policy settings, comparing supply-side measures controlling land-use allocation with demand-side measures controlling bioenergy use. We showed that in a scenario, where climate policy creates a large demand for bioenergy, the specific emissions attributed to a unit of bioenergy produced can be lowered by supply-side emissions regulations in the land use sector. Regulations of bioenergy demand reduce deployment level, but fail to induce a reduction of EF, thus resulting in substantially higher overall mitigation effort and carbon prices to reach climate targets. For instance, increasing the price on terrestrial carbon can decrease the EF, while a bioenergy tax on consumption only reduces the total bioenergy quantity, keeping the EF virtually constant at a high level. A demand-side bioenergy tax fails to steer LUC decisions towards areas with low EF and is not suitable to emulate the uniform carbon price regime across all sectors.

In order to fully capture the impact on direct and indirect land use emissions in the absence of direct regulation of land use, a demand-side bioenergy tax would need to be applied to approximately 25 kg CO_2/GJ_{PE} at the primary energy level (61 kg $CO_2/GJ_{biofuel}$ with 41% conversion efficiency), in order to value fossil and terrestrial emissions equally on a 80-year time horizon. Computed on a shorter time horizon, the EF to be applied is substantially higher (200 kg $CO_2/GJ_{biofuel}$ if evaluated until 2050, see Fig. S3, SI), since most emissions occur upfront, while by far the largest part of the bioenergy is being produced after 2050. This EF for biofuels is even higher than values identified in dedicated studies, which are mostly found to be less than 100 kg CO_2/GJ_{PE} on a 30-year time horizon[21] for biofuels from thermo-chemical conversion.

On the supply side, however, implementing a land-use emission carbon price of only 20% of the price in the energy-system (33$/t CO_2 in 2050) eliminates almost half the bioenergy-induced LUC emissions. A full forest protection scheme is also effective, while conserving only specific land-types is not sufficient due to the flexibility to move agricultural activities[35]. In combination with the ineffectiveness of demand-side measures to reduce the EF of bioenergy, this is a strong argument for a direct regulation of all LU-sector-based emission fluxes as a means to mitigate bioenergy-related LUC emissions. This is in particular compelling, since GHG emissions associated with overall food production need to be reduced substantially to achieve the 1.5° or well below 2° target[48]. It is important to note that the focus of this study was purely on CO_2 LUC emissions. To assess the whole value of bioenergy for climate change mitigation strategies (including also e.g. N_2O emissions from fertilization of bioenergy crops[49]), other adverse side effects (such as unsustainable freshwater use or higher food prices) but also benefits from fossil fuel substitution need to be considered as well.

Our study confirms that LUC emission pricing is an effective and efficient instrument to regulate LUC emissions even under large-scale deployment of bioenergy. However, we also show that those policies cannot be emulated by demand-side regulation of bioenergy use, raising the question to what extent the land-use sector can be effectively regulated to make large-scale bioenergy use sustainable. The literature points to numerous challenges for regulating land use, ranging from MRV to the need for huge institutional capacity[50–52]. Moreover, the distributional implications of regulating land-use emissions affect land tenure and livelihoods, raising strong equity and political economy concerns[28,29]. Hence, the policy challenge is to either comprehensively regulate the LU sector and produce biomass at scale or reduce bioenergy demand. The main driving force behind this challenge is the huge demand for non-electric energy, particularly transport fuels. Thus, broad and deep electrification of end-uses would lower the pressure on the land-system and bypass the regulatory gaps in the land-use sector[53].

Methods

General. To assess the impact of bioenergy and to fully cover feedback effects between LUC CO_2 emissions and bioenergy-demand, we use the coupled integrated assessment modeling framework REMIND-MAgPIE.

REMIND 2.1.2 is an open source global multi-regional Ramsey-type general equilibrium model of economic growth with a detailed representation of the energy sector, hard-coupled to the macro-economic core[43,44]. Using optimization methods, it finds a market equilibrium while maximizing intertemporal global welfare. Via different conversion routes REMIND represents the supply, trade and conversion of biomass feedstocks along the value chain to final energy carriers along with relevant GHG emissions and removals. Therefore, the REMIND model values the energy and the carbon content of biomass feedstocks given the market conditions and the regulatory framework. In climate change mitigation scenarios most of the biomass is converted into bio-liquids.

MAgPIE v4.2.1 is an open source global multi-regional partial equilibrium model of the land-use sector that models land-use dynamics spatially explicitly using recursive dynamic optimization[45,46]. The model covers two types of modern (2nd generation) bioenergy production, namely *grassy* and *woody* biomass. Since irrigation of bioenergy crops leads to unsustainable freshwater use[11], we only allowed for rain fed production.

Both models are soft-coupled, balancing prices and quantities of bioenergy feedstocks and GHGs[4]. The main policy instrument to meet a given climate target is a pricing of GHG emissions. GHG prices that are by default applied to all types of GHGs from all sectors and sources are derived in REMIND and passed to MAgPIE so as to meet the predefined GHG budget in 2100 of total energy- and LU-sector based CO_2 emissions. All scenarios in this study are derived with middle of the road assumptions on socioeconomic drivers (SSP2) and meet a global CO_2 emissions budget of 1000 Gt CO_2 to total energy- and LU-based CO_2

emissions from 2018 to 2100, allowing for a temporary overshoot. This budget is derived by subtracting 100 Gt CO_2 emissions due to earth system feedback from the remaining carbon budget of 1170 given in Rogelj et al.[41] (67th percentile for the 2°C target), arriving at 1070 Gt CO_2. As safety margin, this value is rounded down to 1000 Gt CO_2.

Carbon prices. In the *UCP* scenario all types of GHG emissions from the energy and the LU sector are charged with a uniform carbon equivalent price $P_{\mathrm{GHG}}(t, r)$ in $[\$/\mathrm{t\ CO_2}]$ that is increasing with time t. Prices can differ between modeling regions r before 2050 for reasons of inter-regional equity, but they will eventually converge to a globally harmonized prices until 2050[39]. In scenarios with a partial LU price (*LUprice10%-50%*) the price on GHG emissions in the LU sector is reduced for every time step and every modeling region to the corresponding fraction of the respective price level on energy system related GHG emissions (e.g. to 10%).

In order to be consistent with the narrative of a largely unregulated Agriculture, Forestry and Other Land Use sector (AFOLU), we assumed that in scenarios without a price on CO_2 emissions from LUC (*noLUreg*, *protForest*, *protPrimforest*, *protBH*, *protCPD*, *protFF*, *protLW* and *bioTax* scenarios) also non-CO_2 GHGs are exempted from the GHG price in the LU sector. This has the side-effect that these scenarios also involve substantially higher non-CO_2 GHG emissions from agricultural activities compared to scenarios with a carbon price, in particular CH_4 and N_2O. As a result, radiative forcing levels and resulting global mean temperature responses can differ between scenarios, even though cumulative CO_2 emissions coincide. However, since agricultural CH_4 emissions are not related to bioenergy production and N_2O emissions from grassy bioenergy production are negligible compared to LUC CO_2 emissions (see Fig. S4, SI, for a comparison), we omit the effect of non-CO_2 GHG emissions for assessing the impact of bioenergy. Nevertheless, differences between scenarios in global mean temperature in 2100 as a result of varying LU-related CH_4 and N_2O emissions (derived with MAGICC 6[54]), are only in the range of less than 0.2 K (see Fig. S16, SI).

Land protection. In scenarios with explicit land-protection schemes (*protForest*, *protPrimforest*, *protBH*, *protCPD*, *protFF*, *protLW*) we removed the respective areas from the land-pool that is potentially available for any agricultural activities. In Fig. S9 - Fig. S14 in the SI, the protected areas are depicted. *protForest* is a scenario in which all primary and secondary forests are protected, which is a total area of 3683 Mha, while in *protPrimforest* only primary forests with a total area of 1339 Mha are removed from the land-pool. The other land-protection policies only affect some focus areas. In *protBH* Biodiversity Hotspots, in *protCPD* Centers of Plant Diversity, in *protFF* Frontier Forests and in *protLW* Last Wild areas are protected[55]. These focus areas cover areas of 909, 651, 1084 and 3635 Mha respectively.

Additionally, in all scenarios specific land areas are protected or dedicated for afforestation according to the Nationally Determined Contributions (NDC) targets of the nations that are participating in the Paris climate agreement.

Bioenergy tax. As explained above, the default policy assumption regarding the pricing of emissions is a uniform carbon price on both energy- and LU-based GHG emissions. Emissions related to bioenergy-production are thus already penalized directly within the LU sector, which is why the energy system by default treats bioenergy as a carbon neutral energy carrier. In the scenarios with demand-side policies (*bioTax*) we assign an *ex-ante* emission factor ($EF_{\text{ex-ante}}$) to bioenergy that should reflect *potential* bioenergy-related GHG emissions on a global average. $EF_{\text{ex-ante}}$ represents emissions on a global average and is equal for each economic region r and time step t. It directly transforms into a bioenergy tax $T_{\text{bio}}(t,r)$ via the price on GHGs $P_{\text{GHG}}(t,r)$

$$T_{\text{bio}}(t,r) = EF_{\text{ex-ante}} \cdot P_{\text{GHG}}(t,r) \qquad [\$/\text{GJ}_{\text{PE}}]$$

which is applied to every unit of dry matter biomass, i.e. at the level of primary energy (PE). Since the literature and the results of the present study indicate that specific emissions attributed to a unit of bioenergy are highly uncertain even on a global average, we explore the effect of different values of $EF_{\text{ex-ante}}$ ranging from 10 to 50 kg CO_2/GJ_{PE}, which translates to 24 to 122 kg $CO_2/GJ_{biofuel}$ (41% energy conversion efficiency). It is worth noting that $EF_{\text{ex-ante}}$ is in general not equal to the actual emissions that are eventually attributed to bioenergy and which are derived *ex-post* from our scenarios ($EF_{\text{ex-post}}$).

Please also note that in most other publications applying the REMIND model bioenergy is actually charged with a "sustainability tax" that reduces the demand for bioenergy irrespective of the policy design to reflect uncovered externalities, such as unsustainable water usage, food price increase, the loss of biodiversity and nitrogen losses to the environment[39]. In the present study, however, we deactivated this tax, since we wanted to assess the impact of bioenergy given a certain policy assumption in an otherwise uncontrolled market.

Ex-post emission factor. Due to iLUC induced by bioenergy production it is intrinsically impossible to disentangle LUC CO_2 emissions related to bioenergy production from LUC emissions that result from other agricultural activities such as an expansion of crop land or pasture. For each policy setting p we therefore first derive a counterfactual scenario that depicts a world, in which purpose grown bioenergy production is not allowed (bioOff) – a similar approach has been applied for example in Daioglou et al.[23] and Pehl et al.[19] By comparing the actual policy run, in which bioenergy production is activated (bioOn), with this counterfactual scenario, we can reveal the effect that bioenergy has on the coupled energy-LU-system for a given policy assumption p. The *ex-post* emission factor comprising all LUC CO_2 emissions attributed to bioenergy production is then given by

$$EF_{\text{ex-post}}(p) = \frac{E_{\text{bioOn}}(p) - E_{\text{bioOff}}(p)}{B_{\text{bioOn}}(p)} \qquad [\text{kg CO}_2/\text{GJ}]$$

where E_{bioOn} and E_{bioOff} are the total LUC emissions that emerge over the period from 2020 to 2100 for the scenario with bioenergy on and off, respectively. B_{bioOn} is the total amount of purpose grown lignocellulosic biomass produced globally over the same period. Please note that while $EF_{\text{ex-post}}$ is usually expressed in terms of CO_2 emissions per unit of biofuel, to make it comparable with fossil fuels, the thermo-chemical conversion to liquid fuels is subject to substantial conversion losses (the energy conversion efficiency for second generation biofuels (Fischer-Tropsch diesel) is only 41%). Other energy carriers derived from biomass, in particular electricity or hydrogen, exhibit different emission factors due to different energy conversion efficiencies.

EFs are also evaluated spatially disaggregated. For our study the LU model MAgPIE was applied using 1000 distinct simulation units r_{MAgPIE} revealing individual patterns of agricultural activities. Each simulation unit represents a cluster of aggregated 0.5-degree resolution grid cells with similar properties[45,56] (see Fig. S15, SI) and for each of them an EF can be calculated individually:

$$EF^{\text{loc}}_{\text{ex-post}}(p, r_{\text{MAgPIE}}) = \frac{E_{\text{bioOn}}(p, r_{\text{MAgPIE}}) - E_{\text{bioOff}}(p, r_{\text{MAgPIE}})}{B_{\text{bioOn}}(p, r_{\text{MAgPIE}})} \quad [\text{kg CO}_2/\text{GJ}]$$

There are clusters of grid cells without bioenergy production ($EF^{\text{loc}}_{\text{ex-post}} = \infty$), and others, for which the difference in emissions to the counterfactual scenario is zero or even marginally negative, i.e. a simulation unit r_{MAgPIE} with equal or less emissions than in the scenario without bioenergy. Here the $EF^{\text{local}}_{\text{ex-post}}$ is set to zero.

Please note that, since the EFs are given as the ratio of emissions and bioenergy production, there is no information on the total volume of each of these quantities in the different areas in Fig. 2a. The spatial allocation of LUC emission and bioenergy production quantities is depicted in section “Spatial land-use characteristics” of the SI.

It is also important to again highlight that EFs result from a comparison with a counterfactual scenario, in which bioenergy is not used. This approach can lead to a situation, in which *additional* LUC emissions to the counterfactual scenario are rather small, while baseline LUC emissions from the counterfactual scenario (in the same simulation unit) are already substantial. Bioenergy production is then associated with a relatively small $EF^{\text{loc}}_{\text{ex-post}}$, even though the actually occurring emissions are large. However, since these emissions also emerge in the baseline/counterfactual scenario, in this study they are not attributed to bioenergy.

The BECCS efficiency factor. We defined the efficiency of the CDR potential of BECCS by

$$\eta_{\mathrm{BECCS}} = \left(1 - \frac{E_{\mathrm{bioOn}} - E_{\mathrm{bioOff}}}{CDR_{\mathrm{BECCS,\,bioOn}}}\right) \mathrm{x}\ 100\%,$$

where $CDR_{\mathrm{BECCS,\,bioOn}}$ are all negative emissions associated with BECCS from purpose grown biomass. A scenario without bioenergy-induced LUC would thus imply an efficiency of 100%, while in a scenario, in which bioenergy-related emissions are equal to the CDR saving via BECCS, the efficiency is 0%.

Since bioenergy from residues is allowed in the counterfactual scenarios, we excluded the BECCS emission savings related to residues from the calculation of η_{BECCS}. Please note that this efficiency factor is derived to relate bioenergy-induced LUC emissions to the CDR potential of BECCS. It does, however, not cover other benefits of bioenergy to the energy system, particularly the benefits of substituting fossil fuels by biofuels. On the other hand bioenergy related emissions do not cover all negative effects, as described in the paragraph on the bioenergy tax.

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Author contributions

Leon Merfort performed model experiments, analyzed the scenarios, produced the figures, and lead the writing of the manuscript. Leon Merfort, Nico Bauer, Florian Humpenöder, Gunnar Luderer and Elmar Kriegler designed the study, the scenarios and the analysis. All authors contributed to the development of the models, the presented ideas, and to the text.

Competing interests

The authors declare no competing interests.

Code and data availability

REMIND is open source and available on GitHub. The model version used in this study is 2.1.2, which can be downloaded at https://github.com/remindmodel/remind/releases/tag/v2.1.2.

MAgPIE is open source and available on GitHub. The model version used in this study is 4.2.1, which can be downloaded at https://github.com/magpiemodel/magpie/releases/tag/v4.2.1. Documentation can be found at https://rse.pik-potsdam.de/doc/magpie/4.2.1/.

The results of the scenarios shown in this paper will be archived at Zenodo upon publication of this paper.

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