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Reconciling top-down and bottom-up modelling on future bioenergy deployment

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The Intergovernmental Panel on Climate Change's *Special Report on Renewable Energy Sources and Climate Change Mitigation* (SRREN) assesses the role of bioenergy as a solution to meeting energy demand in a climate-constrained world. Based on integrated assessment models, the SRREN states that deployed bioenergy will contribute the greatest proportion of primary energy among renewable energies and result in greenhouse-gas emission reductions. The report also acknowledges insights from life-cycle assessments, which characterize biofuels as a potential source of significant greenhouse-gas emissions and environmental harm. The SRREN made considerable progress in bringing together contrasting views on indirect land-use change from inductive bottom-up studies, such as life-cycle analysis, and deductive top-down assessments. However, a reconciliation of these contrasting views is still missing. Tackling this challenge is a fundamental prerequisite for future bioenergy assessment.

There is a divergence of views on future bioenergy deployment that is based in disparate epistemic communities. Integrated assessment models (IAMs) project rising deployment of biomass and biofuels in climate change-mitigation scenarios[1,2]. In contrast, life-cycle assessments (LCAs) and partial equilibrium models of land-use change emphasize high up-front greenhouse-gas emissions from direct land-use change (LUC)[3,4] and indirect land-use change (ILUC)[5], and highlight epistemic uncertainties in modelling greenhouse-gas emissions as exemplified in fat-tail distributions and associated high risks[6]. Furthermore, bioenergy deployment is regarded as a threat to carbon-rich natural land, biodiversity, water resources and food security[7]. The Intergovernmental Panel on Climate Change (IPCC)'s *Special Report on Renewable Energy Sources and Climate Change Mitigation* (SRREN)[8] exemplifies the seemingly disparate findings across these communities, highlighting the risk of land-use change and other trade-offs in its chapters on bioenergy[9] and sustainable development[10], without integrating these results in its assessment chapter on mitigation potential and costs[11]. This lack of reconciliation constrains the assessment process and highlights the need for a coordinated research agenda.

We briefly review LCA studies that indicate potentially high but uncertain life-cycle emissions, and highlight that assessments of biofuel emissions often use mixed and inadequate methodologies. We show that IAMs heavily rely on bioenergy to achieve future climate change-mitigation targets. Highly variable modelling assumptions of IAMs allow for widely diverging results. IAMs also focus on first-best world scenarios, that is, they specify assumptions of quasi-perfect worlds, and thus systematically underexplore risks related to ILUC and nitrous oxide emissions in imperfect real-world situations. We provide an outlook of how a modular modelling framework, integrating inductive bottom-up and deductive top-down perspectives, can fill this gap. We argue that improved interdisciplinary communication is necessary to achieve this. We conclude by exploring the implications of a more complete representation of uncertainties at the science/policy interface.

Life-cycle emissions highly uncertain

Life-cycle assessment aims to estimate the total environmental effect of a product or service from cradle to grave. Two general approaches to LCA appear in the literature: attributional and consequential. Attributional LCA relies on static analysis of the supply–use–disposal chain, focusing on material flows, energy use and their direct environmental effects, while ignoring economic interactions. In contrast, consequential LCA examines the environmental effects of a change in production, including market-mediated effects on production and consumption outside the direct supply–use–disposal chain. Including market-mediated effects can substantially alter estimates of environmental outcomes. For example, when ILUC emissions are included, the greenhouse-gas performance is potentially worse for current biofuels than for fossil-fuel systems[12–14].

So far, the integration of economics into the LCA of biofuels has been focused primarily on the narrow question of ILUC-related greenhouse-gas emissions[5,12] while ignoring other market-mediated processes[15]. In most cases, analysts and regulators have simply tacked ILUC emission estimates onto attributional LCA-based estimates of supply-chain emissions, despite the methodological muddle caused by summing average and marginal effects. Other analysts use a different definition of ILUC, based on attribution and correlation, and analyse historical data[16]. Such an approach, however, is inappropriate to explain causal market-based effects. We believe that the next step in the evolution of LCA is a tighter integration with both economic and ecosystem modelling. This could be viewed as turning LCA into a new bottom-up form of integrated assessment modelling.

An example of this type of integration is the analysis by the US Environmental Protection Agency (EPA) for the Renewable Fuel Standard programme under the US Energy Independence and Security Act of 2007. The Renewable Fuel Standard programme mandates the use of biofuels while setting LCA-based performance requirements, which were required by law to include ILUC emissions. Rather than adding ILUC emissions to an attributional LCA

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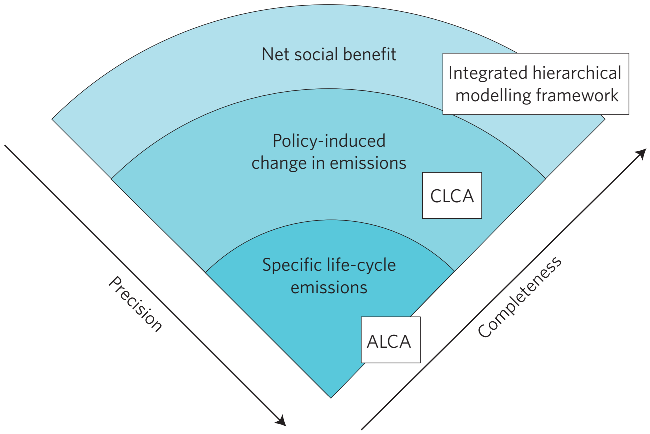

Figure 1 | Precision and completeness of bioenergy evaluation. Attributional LCA (ALCA) can be used for precise evaluation of specific life-cycle emissions for given system boundaries. Consequential LCA (CLCA) is appropriate for analysing the policy-induced change in emissions, but has to deal with significant uncertainties; evaluation so far has been focused on ILUC, that is, only on part of the policy-induced emission change. For complete evaluation, the net social benefit can, in principle, be estimated by an integrated hierarchical modelling framework with high uncertainties and explicit dependency on normative assumptions.

result, the EPA estimated the greenhouse-gas consequences of the entire policy relative to an assumed baseline, with attribution of total effects to specific biofuel categories. The EPA used coupled US and global agricultural sector partial equilibrium models to estimate the total change in crop production globally resulting from the change in biofuels production in the United States. For the domestic United States, the EPA modelled competition between numerous crops and forestry, while tracking changes in emissions and carbon stocks using bottom-up, process-based accounting. For outside the United States, the EPA computed changes in agricultural land allocation, multiplying changes in activities (for example, on-farm energy use, fertilizer, rice and livestock production, and land-use change) by emission factors to compute the total change in greenhouse-gas emissions. This approach eliminates any distinction between direct and indirect effects, or feedstocks and their co-products; the result is a new economic equilibrium with a net global change in greenhouse-gas emissions.

One shortcoming of the EPA analysis is that partial equilibrium models are blind to effects in other markets. Price effects on global oil consumption may further diminish the climate benefits resulting from expansion of biofuels[17,18]. Thus, from a climate perspective, the question isn't whether the greenhouse-gas rating of a biofuel is above or below that of petroleum fuel, but whether net climate forcing increases or decreases as a result of producing more biofuels. Petroleum-market-price effects have not yet been evaluated in an integrated framework and have thus far been ignored in fuel regulations.

The uncertainty associated with estimates of life-cycle greenhouse-gas emissions is large, but underappreciated[19]. Market-mediated effects are notoriously difficult to model robustly, leading to substantial challenges for policymakers. Using a reduced-form model of ILUC emissions that included both parameter and model uncertainty, Plevin *et al.* found that the 95% confidence margin for ILUC emissions from US corn ethanol expansion ranged from about 20 to 140 g of CO_2 equivalent (CO_2e) per MJ, that is, from small, but not negligible, to considerably higher than the life-cycle emissions of gasoline[6]. More generally, variations in the choice of system boundaries, reference land, yields and soil nitrous oxide emissions result in wide variations in estimates of biofuel greenhouse-gas emissions[20,21]. For example, nitrous oxide emissions have been found to vary by a factor of >100 from one European Union wheat field to another[21]. In this light, attributional estimates of biofuel greenhouse-gas emissions can be precise but relatively uninformative for policy assessment, whereas consequential LCA estimates are less precise but more complete and potentially policy relevant (Fig. 1).

The SRREN summarizes ranges and estimates of life-cycle emissions of major biofuels for attributional LCA without LUC (Fig. 2.10 in ref. 9) and separately for LUC (Fig. 9.10 in ref. 10) and ILUC (Fig. 2.13 in ref. 9). Owing to a lack of literature on other market-mediated effects, the SRREN could not evaluate these effects and total net greenhouse-gas emissions related to biofuels and other bioenergy. Insights on ILUC emissions were not integrated into the IAMs considered by the SRREN[11].

Advanced biofuels are expected to have lower life-cycle emissions than current biofuels, owing to higher crop yields and the potential to use wastes and residues rather than purpose-grown feedstocks[9]. Life-cycle greenhouse-gas-performance estimates of second-generation biofuels remain uncertain in the absence of large-scale crop production trials and commercial-scale biorefineries[22]. These uncertainties are further reinforced by current modelling practices: as with first-generation biofuels, greenhouse-gas assessments of ligno-cellulosic biofuels use narrow system-boundary settings that generally exclude ILUC emissions and other market-mediated effects. However, if ligno-cellulosic crops displace food, feed, fibre crops or forestry and other ecosystems and their services, they will also induce LUC or ILUC emissions. A consequential assessment indicates that some cellulosic biofuels may lead to a net increase in greenhouse-gas emissions[23]. Other authors scrutinize the low energy density of ligno-cellulosic crops, which might cause the fraction of life-cycle energy used to grow and transport energy crops to be up to five times higher than for grains, indicating significant diseconomies of scale[24]. Such initial evidence suggests the importance of providing adequate incentives to 'do second-generation biofuels right': considering perennial feedstock, forestry residues and co-products, alternative conversion routes, site-specific conditions as well as the induced effects of moving to large-scale production[25]. This preliminary evidence also points towards the crucial question of how to adequately model future technologies in a LCA framework. How much second-generation biofuel will be available by when remains uncertain, as it depends on regulatory frameworks, technological progress and overcoming bottlenecks in the deployment of supporting infrastructure and logistics[26].

IAMs rely on bioenergy

A central goal of IAMs is to identify abatement of greenhouse-gas emissions with minimum costs to meet a prescribed climate constraint, such as a specific carbon dioxide concentration in 2100. IAMs typically identify cost-effective technology deployment under stylized assumptions (for example, competitive markets, complete market clearance, information fully available) usually associated with first-best policies, such as a global price on greenhouse-gas emissions or effective forest-protection schemes. In a first-best policy framework it is assumed that all market failures are cured by appropriate policy instruments.

In IAMs, biomass emerges as a key resource to abate emissions from the energy system. Bioenergy is usually treated as carbon neutral (zero emissions)[2,27]. Life-cycle emissions are an implicit part of the emission factors in models, and ILUC emissions are often ignored or excluded by assumption (but see below). A crucial assumption is the availability of second-generation conversion pathways that increase effective bioenergy yields per land area and reduce emissions from fertilizer use[1,2,28]. If bioenergy can be combined with carbon capture and storage, negative net carbon

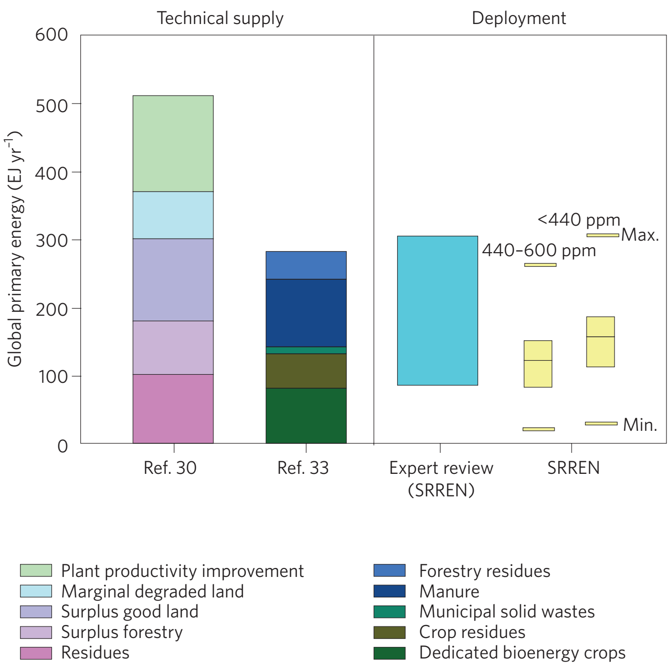

Figure 2 | Technical bioenergy potential and deployment scenarios for 2050. Left: Estimates of the technical potential in biomass primary energy supply are 200–500 EJ (ref. 30) and 160–270 EJ when taking more sustainability constraints into account[33]. Right: An expert review of the SRREN suggests potential deployment levels of 100–300 EJ (ref. 9). Biomass deployment levels from IAMs reveal most likely ranges of 80–150 EJ yr^{-1} for a relatively weak mitigation target (carbon dioxide concentrations by 2100 of 440–600 ppm) and 118–190 EJ yr^{-1} for a relatively ambitious mitigation target (carbon dioxide concentrations by 2100 below 440 ppm).

dioxide emissions can be achieved (carbon sequestration) in a first-best policy framework. Assumptions about the availability of bioenergy with carbon capture and storage greatly improve the greenhouse-gas balance of bioenergy deployment, and are crucial to achieving low-stabilization targets[29].

Bioenergy deployment potential is highly uncertain. The technical potential of bioenergy (possible supply) has been estimated to be up to 500 EJ until 2050 (ref. 30; Fig. 2a). If strict sustainability criteria (forest protection, avoided water and food competition, avoided biodiversity loss) are applied, the sustainable supply of global bioenergy shrinks considerably, with estimates of 34–270 EJ (refs 1,31–34; Fig. 2a). When discussing bioenergy, the SRREN, assuming a technical potential range of roughly 50–500 EJ, suggests a plausible deployment range of 100–300 EJ until 2050 (Fig. 2b), reflecting soil conservation and biodiversity goals as well as potential water scarcity and the use of marginal land for subsistence farming[9]. When discussing climate change mitigation, the IAMs, as considered in the SRREN, project 80–150 EJ of bioenergy to be applied in the energy system for medium-ambitious climate change mitigation (440–600 ppm)[11] (Fig. 2b). In these IAMs, more stringent climate targets require increased biomass deployment[9,27–29,35]: IAMs indicate an application of 118–190 EJ of primary bioenergy for ambitious climate change mitigation (<440 ppm)[11] (Fig. 2b).

Variable modelling assumptions in IAMs. Two main factors determine future bioenergy deployment as projected by IAMs: (1) crop expansion into non-agricultural land and (2) intensification and technological change in the agricultural sector[36]. Assumptions about these factors vary significantly across IAMs. The recent literature tends towards more conservative assumptions on yield, available land area and resulting bioenergy potential than does earlier literature (Supplementary Section SA). The projected area used for energy crops varies between 60 and 3,700 Mha (refs 33,37–39) corresponding to 0.4–28% of the Earth's land surface (excluding Greenland and Antarctica). A number of studies cluster between 240 and 500 Mha (refs 31,40,41). These discrepancies are based on different assumptions about food and fibre demand and associated agricultural production areas, availability of agricultural and forestry residues, constraints of environmental protection, such as avoided deforestation or biodiversity conservation, and the availability of land suitable for cropland expansion.

Similarly, estimates of crop yield per area vary between 7 and 60 MJ m^{-2} yr^{-1} (refs 1,33,40). Most land-use and agricultural sector modelling approaches treat technological change and future yield increases exogenously by assuming exponentially increasing land productivity. The rate of technological change is highly uncertain and is an important contribution to the uncertainty in projected deployment[9,33]. Historically, average yield across all crops has grown about 1.3% annually from 1970 to 1995 (ref. 42). Yield growth rates have declined in the past decades[43], but yield growth potential is still considerable[44]. For example, the Global Change Assessment Model (GCAM)[45] bases assumptions of technological change on short-term projections by the United Nations Food and Agriculture Organization (1.5% per year until 2030 and 0.9% per year until 2050)[46] and 0.25% annual technological improvement for all crops in the second half of the century. Yield and land demand are interdependent: for example, the rate of land-use intensification determines demand for land expansion, all else equal. The Refined Model of Investments and Technological Development (ReMIND)/Model of Agricultural Production and its Impact on the Environment (MAgPIE) treats technological change endogenously — that is, as a function of available land area and demand — projecting yield productivity to increase between 0.6% and 0.9% annually as a function of bioenergy demand and available land[47].

Recent progress in sensitivity analysis. Recent IAMs already include detailed land-use data and competition for land, for example, the GCAM model[45], the Emissions Predictions and Policy Analysis (EPPA) model[48], the Integrated Model to Assess the Global Environment (IMAGe)[1] and the ReMIND/MAgPIE model[47]. Owing to the complexity of IAMs, only a few studies deal with uncertainty explicitly. Uncertainty is represented in a simple sensitivity analysis where one or two parameters are varied to depict a few scenarios. A systematic exploration of the assumption (and solution) space usually remains elusive because of computational complexity. However, recent studies characterized some parameters more comprehensively. For example, some authors explored the implications of different assumptions on climate-system parameters[49], gross domestic product growth[49] and technology costs[50]. Reilly and Paltsev include the land-use sector in the computable general equilibrium framework EPPA, thus establishing a link between energy and land markets[51]. Building on this, Gurgel *et al.* compared land conversion in two different frameworks, one based on observed land supply elasticities and the other based on the direct costs of land conversion[52]. In the direct-cost framework, increased land rents induce higher deforestation than in the supply elasticity framework. Van Vuuren *et al.* scrutinized the sensitivity of bioenergy potentials to assumptions on yield improvements, soil degradation, water scarcity and development of future areas for nature conservation[1]. The results indicate that for their default scenario more than half of the bioenergy potential occurs in areas attributed with severe sustainability concerns, and that assumptions on yield improvements are another dominant determinant of bioenergy potential. A detailed list of IAMs treating uncertainties is given in Supplementary Section SB.

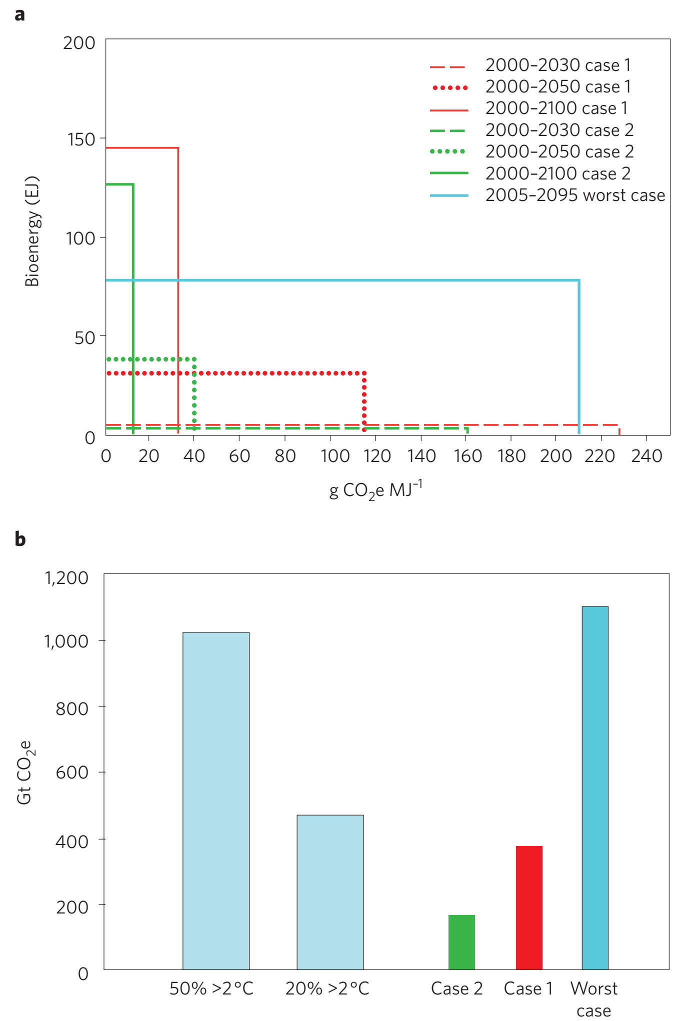

Figure 3 | Greenhouse-gas emissions of bioenergy deployment. **a**, Most IAMs assume no land-use change emissions from bioenergy (0 g CO_2e MJ^{-1}), achieved, for example, by global forest-protection policies. In contrast, in an uncontrolled market, LUC emissions can be huge (area inside coloured lines). Emissions have a distinct temporal pattern: in the short-term (2000–2030) time-averaged specific emissions are high but total deployment is low. In the long run (2000–2100), time-averaged emissions specific emissions are relatively low (between 1/7 of conventional gasoline life-cycle emissions in the optimistic case (Case 2) and 2/7 in the pessimistic case (Case 1)). But even then a high deployment level results in significant absolute emissions. Case 1 and 2 data taken from ref. 48; 2005–2095 worst-case data taken from ref. 49. **b**, Emissions from land-use change and agricultural practice can consume a significant part of the available carbon budget. In Case 1 and 2, 28–65% of a stringent carbon budget (<20% change of global warming >2 °C) is consumed by ILUC and nitrous oxide emissions[48]. It has also been suggested that global deforestation could in the worst case exceed even a generous carbon budget (<50% change of global warming >2 °C)[49].

IAMs focus on first-best scenarios. Although the exploration of modelling assumptions has improved in recent studies, the vast majority of climate change-mitigation scenarios, as evaluated in Chapter 10 of SRREN, make first-best assumptions and take bioenergy availability as exogenous, thus neglecting relevant feedbacks and ignoring ILUC. By modelling first-best worlds, IAMs are instructive in providing optimal benchmark scenarios. For example, IAM scenarios commonly rule out detrimental dynamics (for example, undesirable land-use change[2,27] or cropland expansion into forest areas[28]) by assumption, or limit harmful land-use change by assuming an all-sector carbon cap[28,53]. In such an idealized world, many IAMs depict future bioenergy deployment close to technical potential (Fig. 2). This has become particularly obvious in the scenario assessment conducted in the IPCC's SRREN. In an ensemble of 137 climate change-mitigation scenarios, 135 scenarios included land-use emissions in worldwide carbon pricing[54] — a highly optimistic assumption. Only about ten scenarios considered reduced bioenergy availability[29,55]. IAMs often use simple representations of markets that assume perfect competition and neglect non-market subsistence farming and non-market uses of other environmental goods and services (for example, biodiversity), which can have a considerable impact on future bioenergy markets and their consequences[31].

IAMs insufficiently explore ILUC risk. Bioenergy deployment results in greenhouse-gas emissions from energy-crop production, biomass conversion, and transport of feedstock and fuels. Under increasing scarcity of productive land, the increased food and bioenergy demand may only be accommodated by agricultural intensification, which implies more fertilizer use and higher nitrous oxide emissions[48,56]. IAMs usually exclude significant ILUC effects by assuming the existence of policies that protect forests and restrict energy crops to unproductive land[2,27,28,35]. In contrast, if a global greenhouse-gas cap excludes land-use sectors, very high emissions can result[45,48,54,57] (Fig. 3). Melillo *et al.* explicitly treat profitable land conversion without carbon price or nature protection[48]. In this case, estimates of the corresponding carbon intensity of cellulosic biofuels vary between 13 and 229 CO_2e MJ^{-1} (compared with a carbon intensity of ~96 g CO_2e MJ^{-1} for gasoline)[48]. Lower carbon-intensity values emerge if cropland expansion into natural areas is restricted, and under long evaluation periods. As the evaluation period increases, carbon intensity decreases because total bioenergy production on any given land can eventually compensate for initial LUC emissions by substituting for fossil fuels (Fig. 3a). Although ILUC emissions occur up-front and can be highly significant, nitrous oxide emissions will be more important on longer timescales owing to predicted increases in fertilizer use. When modellers do not assume land-use constraints, ILUC-related emissions can be extremely high (>1,400 Gt CO_2 from 2005 to 2100)[45], potentially exceeding global carbon budgets under strict climate change mitigation[57] (Fig. 3b). Even if excessive land-use change is avoided, ILUC emissions and fertilizer-related nitrous oxide emissions can still consume around 30% of a strict carbon budget (Fig. 3b). High deployment levels of >120 EJ produce significant greenhouse-gas emissions even for low carbon intensities (Fig. 3a,b). The space between the extreme scenarios — in terms of endogenous ILUC, nitrous oxide emissions and imperfectly respected sustainability constraints — remains largely unexplored.

Figure 3 also highlights the question of timescales. IAMs typically evaluate 50–100-yr time spans. The urgency of climate change may however require crucial action on relatively short timescales. Specifically, the high emissions of shorter temporal scales depicted in Fig. 3a indicate a more cautionary evaluation of ILUC and, possibly, other market-mediated effects. Also, on longer timescales, assumptions made on future technologies become entirely speculative.

Comprehensive assessments required

A relevant and comprehensive assessment of the bioenergy potential for climate change mitigation would be characterized by: (1) estimating the marginal and total change of greenhouse-gas emissions associated with bioenergy production; (2) making transparent the full range of plausible assumptions and communicating

Table 1 | Evidence from LCAs that could be operationalized for crude sensitivity analysis in IAMs.

Dimension	Common practice in IAMs	Evidence from empirical studies and LCA models	Good practice and improvements
ILUC	Assumed to be irrelevant in a 'quasi-perfect world'. For example, models assume forest protection and that sugar cane serves as an intermediate, allegedly low-carbon, option, contributing to 90% of production between 2000 and 2025 (ref. 35).	ILUC emissions are uncertain, but potentially highly significant. If cattle intensity in Brazil increases significantly less than 18% between 2003 and 2020, ILUC induced by sugar-cane production may lead to high emissions[13].	Exploration of imperfect worlds. Scenario analysis of land-area expansion with associated ILUC[48,56] under alternative policy regimes.
Nitrous oxide	Focus on carbon dioxide emissions.	Nitrous oxide emissions might negate the climate balance of biofuels and vary significantly with soil and fertilizer application rate[21].	Nitrous oxide co-emissions are included[48,56]. Variability (deployment in different world regions) still needs to be explored.
Land-use data	Land-use data ignores potentially important uses, for example, subsistence farming.	Impact of bioenergy deployment for subsistence farming is unclear.	Top-down and bottom-up model integration for studying subsistence farming. Efforts to improve global data sets.
Yield growth rate	Exponential yield-improvement rate between 0.25 and 1.5% (refs 45,47).	Linear yield increase may be a more plausible assumption than exponential yield increase[7]. Physiological constraints, continued soil degradation and bounded availability of high-quality farmland may limit further yield growth[79].	Model intercomparisons: explore full variability between optimistic technological progress in agricultural practice and possible saturation effects, for example, over a 50-yr horizon, a linear yield increase equal to 1.3% of the year-zero yield projects a yield in year 50 that is 15% lower than is projected by a compounding 1.3% annual increase.
Climate feedback	Not accounted for or emphasis on optimistic carbon dioxide fertilization.	Observations show that yield decreases significantly with higher temperatures[80,81]. Probabilistic estimates of climate feedback point towards negative effects with high uncertainty[82].	Accounting for uncertainty on climate feedbacks, bioenergy potential varies between 63 and 120 EJ (ref. 34). This can be subsumed under yield growth rate (see above).

the resulting uncertainties; and (3) sketching a comprehensive solutions space and its trade-offs on different temporal and spatial scales. Bioenergy assessments have remained short of this task. The current state of bioenergy assessment is insufficient owing to the confusion of average and marginal greenhouse-gas emissions in LCAs, a narrow exploration of the solution space in IAMs and very limited assessments of uncertainties. The SRREN made an important step forward by starting with a systematic exploration of long-term IAM scenarios alongside a detailed evaluation of the LCA literature. However, it failed to reconcile their disparate views. Future bioenergy assessments, including the IPCC's fifth assessment report, should attempt to better integrate the findings of LCA and IAM research communities and help promote increased integration across these communities.

Comprehensively explore solution space with respect to ILUC and other equally relevant trade-offs (for example, water, food and biodiversity). In particular, the risks of ILUC resulting from ineffective forest protection and of uncertain nitrous oxide emissions should be systematically explored in IAMs, following the example of Melillo *et al.*[48] (Table 1). Under these circumstances, the role of second-best supply and demand-side policies, as well as technological solutions for limiting ILUC, can be explored.

Close research gap in consequential assessments. Optimizing bioenergy production chains, the use of perennial feedstock produced on so-called marginal land, and the use of residues from forestry and side products are suggested mitigation strategies. Policy-relevant assessments of such bioenergy use require consequential LCA studies estimating marginal greenhouse-gas emissions. Further consequential LCA studies and methodologies must expand on preliminary knowledge, measuring not only net carbon effects within different policy regimes, but also evaluating critical infrastructural requirements.

Increase level of detail across temporal and spatial scales, market resolution and trade-offs. Detailed bottom-up consequential LCA studies could consider 10-yr time spans and investigate dynamics in countries and regions of particular relevance in terms of their bioenergy supply potential (for example, Brazil, Malaysia) or policy-induced demand-pull (for example, United States, European Union). Detailed market models could investigate the interaction of global bioenergy markets with subsistence farming, investigating the relevance of variability in local practice (Table 1). Trade-offs, for example, between bioenergy deployment and food security, could be further resolved on regional scales and contextualized in a risk or resilience framework. A bidirectional calibration between highly resolved bottom-up models (consequential LCA), retaining details on supply chains, and highly integrated top-down IAMs can make both model classes more policy relevant (Fig. 4).

Provide transparency on uncertainty and underlying assumptions. IAMs should focus on a more complete representation of the uncertainty space and the dependency on crucial assumptions in parameters and model structure, as has been done in

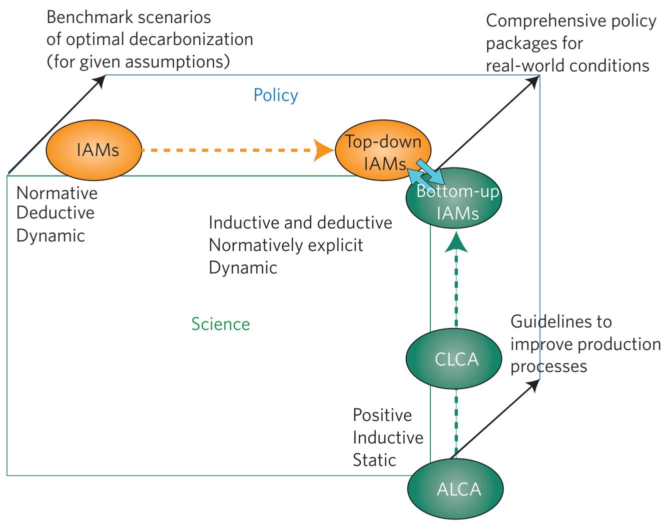

Figure 4 | Towards a hierarchical modelling framework that is policy relevant. IAMs provide a useful benchmark for optimal decarbonization. Attributional LCA (ALCA) results can be used to decrease the carbon footprint of production processes. Consequential LCA (CLCA) results help to identify risks of current bioenergy deployment. A combined effort of detail-rich CLCA becoming bottom-up IAMs, and top-down IAMs calibrated by their bottom-up counterpart (for example, imperfect forest protection and climate policy, potentially tight oil and food markets with rebound effects, climate and land-use constraints for bioenergy production) can provide policymakers with an intuition for comprehensive policy packages, and can identify systemic risks by representing sources of relevant uncertainty.

some consequential LCA studies[6]. With a Monte Carlo simulation applied on the input parameter space, Sokolov *et al.* systematically analysed climate outcomes in an IAM framework[49]. A similar Monte Carlo method could be used to systematically investigate different policy and land-use futures, and their associated greenhouse-gas emissions. Assumptions that define market behaviour (for example, perfect foresight versus incomplete foresight, or complete versus incomplete market clearing) are normative and should be fully explored by systematic variation. The presentation of scenario results should fully acknowledge the uncertain nature of all findings and its conditionality on partially speculative assumptions[58,59].

Scientific communication and open-system boundaries

Improved exchange between bottom-up and top-down communities is a precondition for better understanding benefits and costs of bioenergy deployment for climate change mitigation, and for the broader sustainability question in future assessments. The IAM community has made large steps forward in recent years in integrating energy systems and land-use modelling[45,47,48,53], and exploring a broad set of assumptions. There are, however, a number of potentially relevant dynamics that are not considered by most IAMs (see above and Table 1 for further examples). The main point is that alternative sets of assumptions describing a world with risky trade-offs (ILUC being the case investigated here), are not well reflected. As Robert Socolow puts it[60]: "In understanding climate change, models help us do the imagining, but only if there is a general sharing of provocative runs of models before these runs are lost in an averaging process." For comprehensive assessment, a close collaboration between integrated assessment and bottom-up modellers can account for systemic uncertainties and reduce the speculative character that is inherent in large-scale modelling exercises. A broader cross-disciplinary peer review (consequential LCA analysts reviewing IAM papers, and vice versa) and improved transparency of assumptions and raw data (by publishing all assumed parameter values and formulas as supplementary material) would facilitate research integration. Exposing input data to outside scrutiny and challenge by other experts would expedite the evolution towards more policy-relevant IAMs.

The bioenergy conundrum is representative of a key challenge for sustainability sciences. Only an open-system boundary framework allows an inclusive treatment of potential risks outside of narrow analysis frameworks. An open-system boundary analysis is confronted with a high interdependency between coupled socio-economic biosphere and geosphere systems, and a complexity of scales and dynamics. This challenge necessitates hierarchical and modular models on different scales instead of singular global-solution models, and regular interdisciplinary exchange and work. Inherent uncertainties warrant a shift of focus from representative scenarios to identification of systemic risks.

Bioenergy and the science/policy interface

Our analysis emphasizes that the risks of bioenergy deployment must be explicitly treated at the science/policy interface. Projections of the impact of bioenergy use are inherently uncertain and dependent on value judgments. Facts and values are inseparable[61]. In such a situation society can only progress if there is an open discourse between science, policy and the general public about ends and means. This idea is encapsulated in Jürgen Habermas' "pragmatic model of scientific policy advice"[62], which at present is being applied as an organising principle in the Working Group 3 contribution to the IPCC's fifth assessment report[63]. It is therefore essential that scientists communicate this uncertainty — and the dependence of model projections on idiosyncratic assumptions — to policymakers[64]. Future assessments of bioenergy have the opportunity to make a step forward in this direction by openly communicating varying assumptions, results, risks and uncertainties in the solution space, based on sound communication principles of uncertain climate risks[65]. Policies, in turn, need to be designed cautionary in light of the uncertainty associated with high risks. The uncertainty surrounding the future impact of bioenergy precludes policies based on accurate quantitative greenhouse-gas estimates. The current quantity mandates for biofuels in the United States and the European Union rely on quantified carbon intensities simplifying or excluding hard-to-measure but potentially very significant ILUC and rebound effects[6,66]. Hence, these policies may be ineffective or even harmful with respect to climate-policy goals[67,68]. Instead, policies that favour good practices[69] (such as nitrogen recycling, crop rotation and cascading schemes), and increased research and development in advanced bioenergies[70] should be supplemented with policies that limit the risks of bioenergy deployment. For example, in legislation, the burden-of-proof of low-carbon sustainable biofuels or bioenergy could be shifted to the producer[71]. One way to achieve this would be to debit the carbon release of bioenergy at end use, and to credit the life-cycle sequestration in agricultural production if additionality can be demonstrated[72]. As deforestation is mainly driven by non-bioenergy markets (for example, soybean for animal feed in Brazil[73]), LUC and ILUC safeguard policies are best extended also to other land use and feedstock[74]. To contain high risks, Organisation for Economic Co-operation and Development countries and emerging economies could opt for a demand reduction in high-impact food and fuel markets by charging full social costs, producing considerable co-benefits in public health and environmental amenities[75,76]. Analysis of individual markets suggests that demand management could substantially reduce pressure on scarce global land sources and may be the most practicable and effective option[77,78].

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Additional information

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