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Bioenergy in the IPCC Assessments

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From the First (in 1990) to the Fifth (in 2014) IPCC Assessment Reports (which denote as AR1 to AR5 here, though at the time they were designated as FAR, SAR, TAR and then AR4 and AR5), the level of detail and quantification of potentials and impacts of bioenergy have increased significantly, and this largely reflects the increase in available literature on the topic. Figure 1 shows the papers published on Web of Knowledge database between 1990 and 2017 on bioenergy/biofuels and the subject areas in which these articles were published. With ~6000 papers published each year on bioenergy since the last assessment report (Fig. 1a), the task of synthesizing this vast literature, across a diverse range of disciplines (Fig. 1b), has become ever more challenging.

Below, we describe how the treatment of bioenergy and biofuels has changed over the history of the IPCC, as tracked through AR1 to AR5, including the Special Report on Renewable Energy (SRREN). The Special Report on Land Use, Land-Use Change and Forestry (2000) was also considered, but does not cover bioenergy. Table 1 shows the number of pages dedicated to bioenergy/biofuels in IPCC reports and the percentage of total pages in each volume dedicated to bioenergy/biofuels. The number of pages dedicated to bioenergy/biofuels has increased between AR1 and AR5.

More space has been dedicated to bioenergy/biofuels in subsequent IPCC Assessments, with <0.04% of total volume pages in AR1, rising to 1.5% of all pages for AR5 (Table 1). For the SRREN (which only deals with renewable energy), one whole chapter (~10% of total report pages) was dedicated to bioenergy (Table 1). In AR1 and AR2, the term biofuel was used to denote both liquid and solid forms of bioenergy, while from AR3 onwards, biofuel tended to be used to mean liquid transport fuels, while bioenergy was used as the more generic term to cover all energy from biomass.

Perhaps, the most important changes between AR1 and AR5 are (i) the degree of quantification of the global mitigation potential bioenergy and (ii) the increase in diversity of bioenergy options considered, for example from simple consideration of wood for energy in AR1 to consideration of bioenergy with carbon capture and storage (BECCS) in AR5.

AR1 WGII (Parry *et al.*, 1990) noted that short rotation forestry might be a form of alternative energy. The potential use of biomass to replace fossil fuels for energy generation is referred to in AR1 WGIII (Kupfer & Karimanzira, 1990), and biofuel plantations are mentioned twice, but there is no quantification of potential.

In AR2, WGII covered bioenergy in the chapter on Agricultural Options for Mitigation of Greenhouse Gas Emissions (Cole *et al.*, 1995). Around three pages were used to discuss dedicated biofuel crops, bioethanol and biodiesel, and crop residues, and the first estimates of global potentials were included, at 300–1300 MtC yr⁻¹ of fossil fuel carbon offsets for biofuels, with an additional 100–200 MtC yr⁻¹ from crop residues, giving a total (in CO₂e) of 1470–5500 MtCO₂e yr⁻¹.

Unlike AR1 and AR2, the WGIII volume of AR3 had no sectoral chapters and included economic assessments of mitigation potential for the first time. Discussion of bioenergy occurred in two chapters, Ch3 on Technological and Economic Potential of Greenhouse Gas Emissions Reduction (Moomaw *et al.*, 2001) in section 3.6 on agriculture and energy cropping and in Ch4 on Technological and Economic Potential of Options to Enhance, Maintain, and Manage Biological Carbon Reservoirs and Geo-engineering (Kauppi *et al.*, 2001) in section 4.3.3 on Opportunities in agricultural land. Energy cropping was estimated to have a global potential (in 2020 at 0–100 US\$ per tCeq.) of 1300–2750 MtCO₂eq yr⁻¹ (converted from original units of MtC yr⁻¹).

In AR4, bioenergy was considered in the chapter on Agriculture (Smith *et al.*, 2007). Global bioenergy mitigation potential (from fossil fuel substitution) was estimated to be 70–1260 MtCO₂-eq yr⁻¹ at up to 20 US\$ per tCO₂-eq, and 560–2320 MtCO₂-eq yr⁻¹ at up to 50 US\$ per tCO₂-eq. A potential of 2720 MtCO₂e yr⁻¹ was reported for prices above 100 US\$ per tCO₂-eq.

Bioenergy received thorough treatment in the SRREN (Chum *et al.*, 2011) with 92 pages dedicated to the topic. BECCS appears for the first time, but with only 27 lines on the chapter dedicated to the topic and no estimated potential for BECCS. The SRREN notes that electricity generation from biomass could reach 1220 Mt CO₂eq by 2030, much of which at costs <20 US\$ per tCO₂eq. The estimates of mitigation potential for bioenergy from the energy systems models are the same as those reported

10th Anniversary Editorial/Perspective.

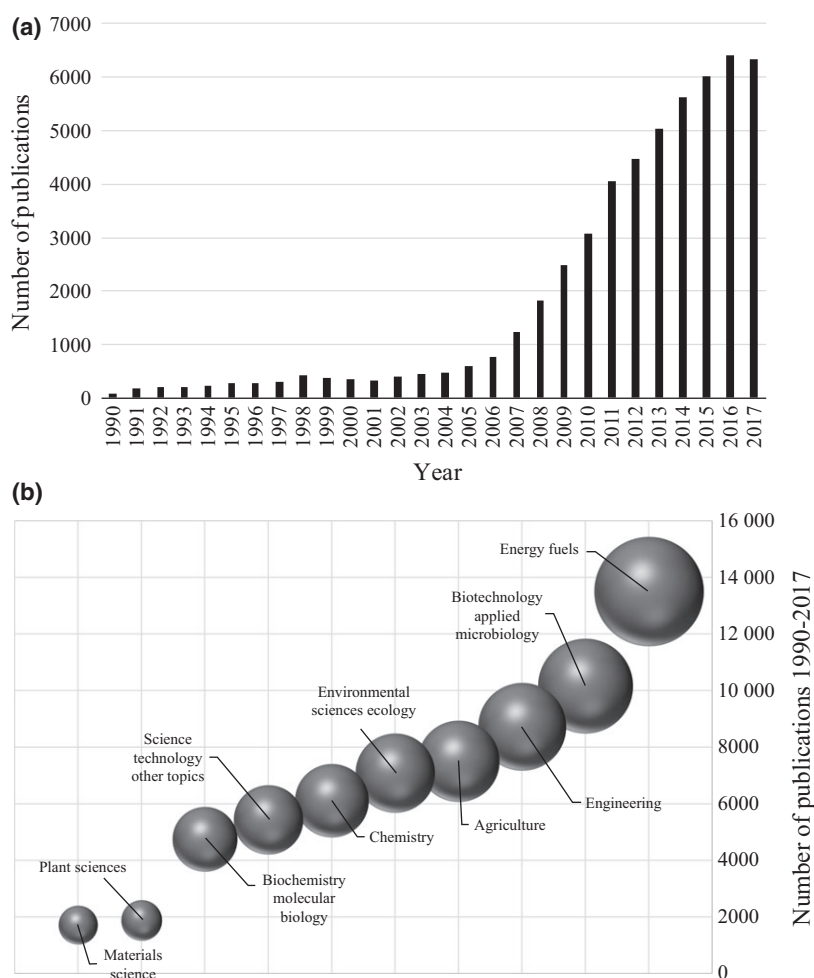


Fig. 1 (a) Papers in Web of Knowledge 1990–2016 on bioenergy or biofuels using the search term ‘bioenergy* or biofuel’ to provide an index of publication activity on these topics. The search was carried out on 14 March 2018; (b) top 10 subject areas under which the bioenergy and biofuel papers appeared. The size of a bubble represents the number of publications in an area.

in AR4, that is 70–1260 Mt CO₂eq yr⁻¹ for costs of <~200 US\$ per tCO₂eq. and 560–2320 Mt CO₂eq yr⁻¹ at ~50 per t CO₂eq. Of these totals, the overall mitigation from biomass energy from the forest sector was estimated to reach 400 MtCO₂ yr⁻¹ to 2030 (Chum *et al.*, 2011).

In AR5, the WGIII chapter on Agriculture, Forestry and Other Land Use (Smith *et al.*, 2014) had a dedicated section on bioenergy, totalling 15 pages of that chapter. Total mitigation potentials were not given, although the estimates for energy generation of 95 EJ yr⁻¹ in 2030 and 245 EJ yr⁻¹ in 2050 equate roughly to 5100–13 200 MtCO₂e yr⁻¹ using conversion factors of Hall & Scrase (1998). BECCS also featured strongly in the chapter Assessing Transformation Pathways (Clarke *et al.*, 2014) which included the modelled scenarios of pathways to achieve climate stabilization at 2 °C above pre-industrial levels. In assessing the overall potential for BECCs by

analysis of the IPCC AR5 WGIII scenarios database, Smith *et al.* (2016) reported a mean level of implementation of BECCS at 12 100 MtCO₂e yr⁻¹ in 2100 for scenarios consistent with a 2 °C target, with Clarke *et al.* (2014) reporting the full range as 0–22 000 MtCO₂e yr⁻¹. The consideration of BECCS, and the specific focus on scenarios showing a very high level of mitigation ambition (to meet a 2 °C target), means that the potential range reported in AR5 was much larger than in any previous assessment report or the SRREN.

Estimates of ranges of global mitigation potentials for bioenergy from AR1 to AR5 (including SRREN) are summarized in Figure 2.

While quantification has improved since AR1, wide ranges for estimated mitigation potential of bioenergy remain, as there are many sources of variation, which all contribute to the overall uncertainty (e.g. assumptions about land area available, yield and technology

Table 1 Space dedicated to bioenergy/biofuels in AR1 to AR5 and the SRREN

	AR1*	AR2†	AR3‡	AR4§	SRREN¶	AR5**
Year	1990	1995	2001	2007	2011	2014
Pages on bioenergy††	0.1	3	4	1.5	92	19
Pages on bioenergy as a percentage of all relevant volume pages‡‡	0.0	0.4	0.6	0.2	9.7	1.5

WG denotes the IPCC working group responsible/volume in which the relevant sections appear, which are as follows: *for AR1: WGII – Ch2 Agriculture and Forestry and WGIII – Ch4 Agriculture, Forestry and other human activities. Section on agriculture response strategies; †for AR2: WGII – Ch23 Agricultural Options for Mitigation of Greenhouse Gas Emissions; ‡for AR3: WGIII – Ch3 Technological and Economic Potential of Greenhouse Gas Emissions Reduction – section 3.6 on agriculture and energy cropping plus Ch4 – Technological and Economic Potential of Options to Enhance, Maintain, and Manage Biological Carbon Reservoirs and Geo-engineering – section 4.3.3 on Opportunities in agricultural land; §for AR4: WGIII – Ch8 – Agriculture; ¶for the SRREN, Chapter 2 dedicated to Bioenergy; **for AR5: WGIII – Ch11 – Agriculture, Forestry and Other Land Use (AFOLU) section 11.13 and Ch6 – Assessing Transformation Pathways. ††excludes reference section. ‡‡excludes all annexes.

improvements, improvements in conversion technologies, speed of development of infrastructure; Fig. 2). While uncertainty is difficult to quantify numerically, it has been possible since AR4 to attach uncertainty language statements to most components of the bioenergy mitigation potential estimates.

Looking forward to the IPCC AR6 cycle (including the Special Report on 1.5 Degrees, the Special Report on Climate Change and Land, and AR6 itself), key emerging issues are likely to be (i) trade-offs between the use of land for bioenergy production, food and fibre production and conservation of ecosystem integrity and (ii) the codelivery of bioenergy based climate change

mitigation (with or without CCS and the UN Sustainable Development Goals).

The Special Report on 1.5 Degrees will be delivered in 2018 and will include a critical appraisal of the feasibility of using bioenergy (specifically BECCS) in delivering the 1.5 °C target, and the Special Report on Climate Change and Land, which will be delivered in 2019, will consider an even wider range of issues, including how bioenergy and BECCS impact and are impacted by, desertification, land degradation and food security – and the cobenefits and adverse side effects with climate mitigation, adaptation and sustainable land management. The two Special Reports will

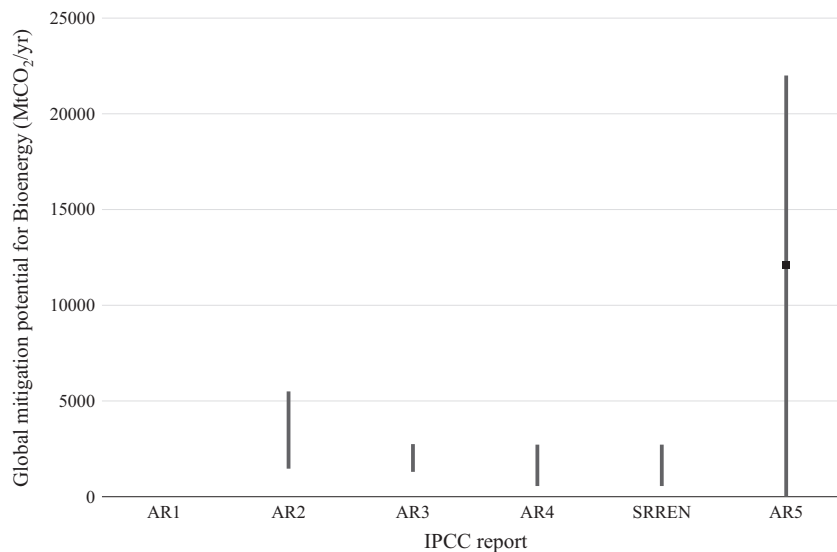


Fig. 2 Estimates of total global mitigation potential of bioenergy in AR1 to AR5 including SRREN (after conversion to common units), showing quoted global potentials. Ranges are shown where given (for different carbon prices from AR3 onwards), and the point in the range for AR5 corresponds to the mean potential for BECCS in 2100 for scenarios consistent with a 2 °C target from the IPCC AR5 WGIII scenario database (Smith *et al.*, 2016). Note that the AR2 values had no target year, AR3 values were for 2020, AR4 and SRREN values were for 2030, and AR5 values were for 2030 and 2050. The range and mean value for AR5 are for BECCS, while for all other reports, the mitigation potential is derived from fossil fuel offsets available from bioenergy.

set the scene for the AR6 report, which is due to be delivered in 2021.

Bioenergy continues to feature prominently in the AR6 cycle, but if anything, has become ever more controversial since it was first treated qualitatively in AR1.

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