The Global Bioenergy Resource

Dr Raphael Slade†, Dr Ausilio Bauen†, Dr Robert Gross†

Using biomass to provide energy services is a strategically important option for increasing the global uptake of renewable energy. Yet the practicalities of accelerating deployment are mired in controversy over the potential resource conflicts that might occur, in particular conflicts over land, water, and biodiversity conservation. This calls into question whether policies to promote bioenergy are justified. Here we examine the assumptions on which global bioenergy resource estimates are predicated. We find there is a disjunct between the evidence that global bioenergy studies can provide and policy makers' desire for estimates that can straightforwardly guide policy targets. We highlight the need for bottom-up assessments informed by empirical studies, experimentation, and cross disciplinary learning in order to better inform the policy debate.

1 Conflicting aspirations for bioenergy

Using biomass to provide energy services is one of the most versatile options for increasing the global uptake of renewable energy and an important component in many climate change mitigation and energy supply scenarios[1-4]. The International Energy Agency (IEA), for example, estimates that biomass could contribute an additional 50EJ (~10%) to global primary energy supply by 2035, and states that "the potential supply could be an order of magnitude higher" [4]. Governments of the world's largest economies have also introduced policies to incentivise bioenergy deployment, motivated by concerns about energy security and climate change, and by the desire to stimulate rural development[5,6]. Yet the potential contribution from biomass to global energy supply is controversial. Sources of contention include concern about the inter-linkages between biomass, bioenergy and other systems. Most notably, land and resource conflicts are foreseen between bioenergy and food supply, water use, and biodiversity conservation. The fear is that the benefits offered by increased biomass use will be outweighed by the costs[7-10]. It is also argued that the wide range of estimates of biomass potential and the lack of standardised assessment methodologies confuses policy makers, impedes effective action and fosters uncertainty and ambivalence[11]. These broad points contribute to a general sense of unease about the future role of bioenergy, and whether it presents a genuine opportunity or is a utopian (or for some dystopian) vision that stands little chance of being realised.

Here we analyse how scenarios for increasing bioenergy deployment are contingent on anticipated demand for food, energy, and environmental protection, and expectations of technological advances. We use a systematic review methodology[12,13] to identify and analyse the most influential estimates of the global bioenergy potential that have been published over the last 20 years. The technical and sustainability assumptions that lie behind these estimates are exposed and their influence on calculations of potential described.

†Centre for Energy Policy & Technology, Imperial College London, 14 Princes Gardens London, 14 Princes Gardens, South Kensington, London, SW7 1NA

We find that the range of estimates is primarily driven by the choice of alternative assumptions and that estimates should be viewed as *what if* scenarios rather than forecasts or predictions. Larger estimates, however, invariably require more stretching assumptions.

The most controversial and influential assumptions relate to the future role of energy crops. We examine these assumptions, focussing on yield predictions, water availability and sustainability assurance. We find that studies provide limited insight into the level of deployment that might be achievable in practice and this highlights the need for caution in using global estimates to justify political intervention.

Finally, we highlight the need for better evidence including bottom-up assessments informed by empirical studies, experimentation, and learning-by-doing in order to better inform the policy debate.

2. Estimating the global biomass resource

The global availability of biomass and how it might be used to provide energy services cannot be measured directly, it can only be modelled. Models vary in complexity and sophistication, but all aim to integrate information from sources such as the Food and Agriculture Organisation's (FAO) databases, field trials, satellite imaging data, and demand predictions for energy, food, timber and other land-based products, to elucidate bioenergy's future role. The least complex approaches use simple rules and judgment to estimate the future share of land and residue streams available for bioenergy. The most complex use integrated assessment models which allow multiple variables and trade-offs to be analysed.

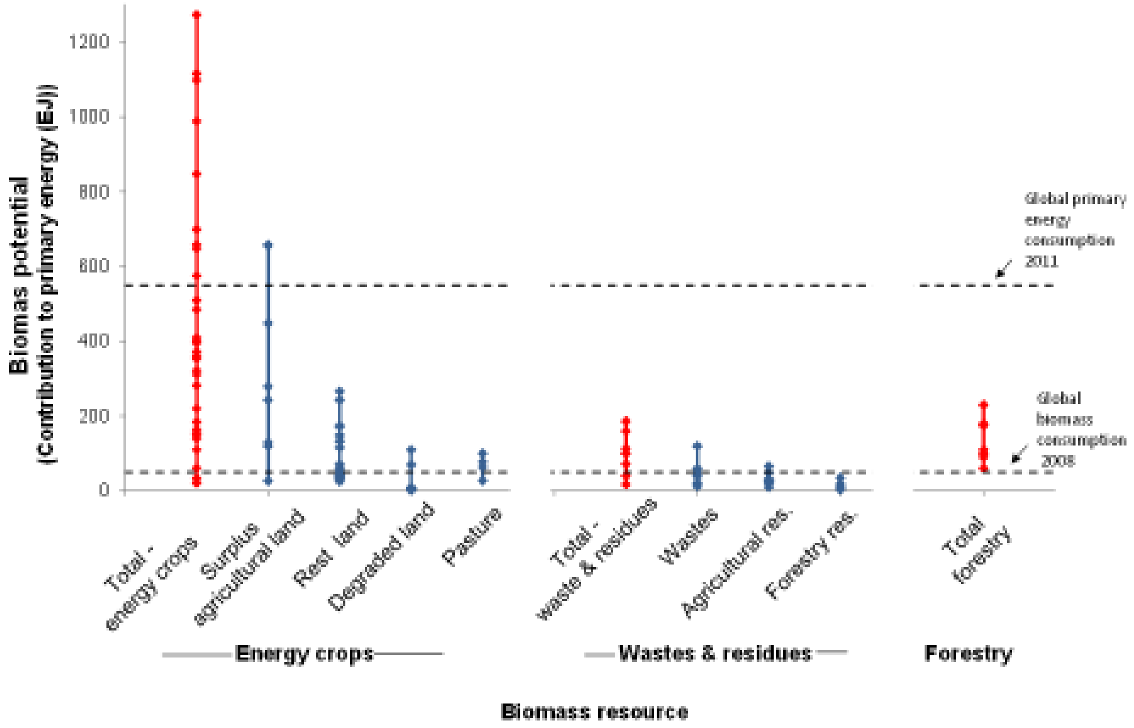
Although models differ greatly in scope and sophistication, the future supply of biomass in all cases depends on the availability (and productivity) of land for energy crops and food, and the accessibility of residues and wastes from existing and anticipated economic activity. Land availability is strongly influenced by assumptions about the area that should be set aside for nature conservation, along with population and diet scenarios – a vegetarian diet, for instance, requires less land than one rich in meat and dairy. Land productivity is strongly influenced by technology scenarios. Particularly important is the potential to increase crop yields and close the gap between optimal yields and those achieved by farmers when faced with environmental constraints such as water and nutrient scarcity, soil degradation, and climate change[14-16].

Modelling results are most often discussed in terms of a hierarchy of potentials: *theoretical* > *technical/geographic* > *economic* > *realistic/implementable*. These terms are not always used consistently, and so results for different studies need to be normalised before they can be compared. Here we compare estimates on the basis of the gross energy content of the biomass (assuming a calorific value of 18GJ per oven dry tonne (odt)) and the major technical and environmental assumptions on which they are predicated.

Our systematic review identified 90 studies. Of these 28 contained original analysis describing over 120 estimates for the future contribution from biomass to global energy supply[1,14,16-41]. The majority of these estimates are for 2050, reflecting the importance of this date in much of the modelling and scenario analysis that has been done over the last 10 years. A detailed analysis of these studies provides the evidence base for this Review (see Supplementary Tables 1-4).

The most important potential sources of biomass are *energy crops (22-1272EJ)*, *agricultural residues (10-66EJ)*, *forestry residues (3-35EJ)*, *wastes (12-120EJ)*, and *forestry (60-230EJ)*, summarised in Figure 1. Not all studies include all these categories in their analysis. In particular, biomass extraction from forests is not considered by many authors because of concern about the potential impacts on biodiversity and carbon stocks. By way of comparison, the total human appropriation of net terrestrial primary production (including the entirety of global agriculture and commercial forestry) is around 320EJ, of which 220EJ is consumed and 100EJ discarded as residues or otherwise destroyed during harvest[42]. This is considerably less than current global primary energy supply (~550EJ).

Figure 1. The range of estimates for the potential contribution of energy crops, wastes and forest biomass to future energy supply. Estimates include unconstrained values. Surplus agricultural land includes good quality land released from food production because yield growth exceeds demand (also called abandoned land in some studies). Rest land includes: savannah, extensive grassland, and shrubland. Degraded land may also be defined as low productivity or marginal land. Land categories cannot be considered fully mutually exclusive. Waste includes dung, municipal and industrial waste. Forestry describes harvest of a fraction of the global annual forest growth increment. Forestry is a highly aggregate category defined by the FAO as areas spanning more than 0.5ha with trees higher than 5m. Some studies make further distinctions between primary forests and plantations.



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† Centre for Energy Policy & Technology, Imperial College London, 14 Princes Gardens London, 14 Princes Gardens, South Kensington, London, SW7 1NA

3. Critical assumptions

Biomass potential estimates can be broadly divided into those that test the boundaries of what might be physically possible, and those that explore the boundaries of what might be socially acceptable or environmentally responsible. Through a detailed examination of each estimate we have identified the key assumptions that determine why bioenergy resource modellers reach such dramatically different conclusions. We describe the most important combinations of assumptions below, and they are summarised in Figure 2.

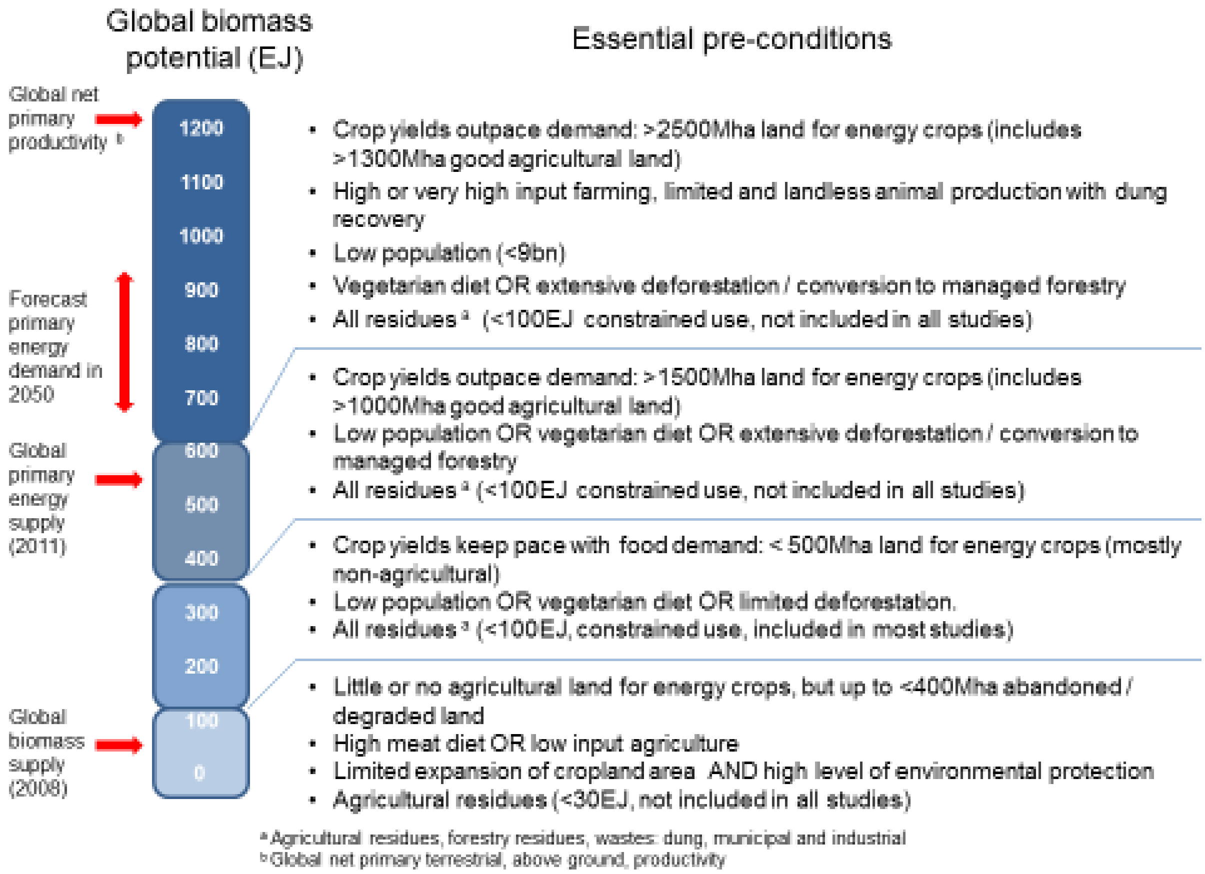
Estimates up to ~100EJ (around 1/5th of current global primary energy supply) assume that there is limited land available for energy crops. This assumption is driven by scenarios in which there is a high demand for food, limited productivity gains in food production, and limited expansion of land under agriculture. Diets are assumed to evolve along the existing trend for increasing meat consumption. The contribution from energy crops (8-71EJ, ~140-400Mha) predominantly comes from agricultural land identified as abandoned, degraded or deforested, and from limited expansion of energy crops onto pasture. The contribution from wastes and residues is considered in only a few studies, but where included the net contribution is in the range 17-30EJ. Most studies in this range exclude biomass extraction from non-commercial forestry.

Estimates falling within the range 100-300EJ (roughly half current global primary energy supply at the top end), all assume that increasing food crop yields keep pace with population growth and the trend for increased meat consumption. Limited good quality agricultural land is made available for energy crop production, but these studies identify areas of natural grassland, marginal, degraded and deforested land ranging from twice to ten times the size of France (100-500Mha) yielding 10-20odt.ha^{-1}. In scenarios where demand for food and materials is high, achieving biomass potentials in this range implies a decrease in the global forested area (up to 25%), or replacing mature forest with young more rapidly growing forest. The majority of estimates in this range also rely on a larger contribution from residues and wastes (60-120EJ). This is partly achieved by including a greater number of waste and residue categories in the analysis, and partly by adopting more ambitious assumptions on recoverability.

Estimates in excess of 300EJ and up to 600EJ (600EJ is slightly more than current global primary energy supply) are all predicated on the assumption that increases in food-crop yields could significantly outpace demand for food, with the result that an area of high yielding agricultural land the size of China (>1000Mha) could be made available for energy crops. In addition, these estimates assume that an area of grassland and marginal land larger than India (>500Mha) could be converted to energy crops. The area of land allocated to energy crops could thus occupy over 10% of the world's land mass, equivalent to the existing global area used to grow arable crops. For most of the estimates in this range a high meat diet could only be accommodated with extensive deforestation. It is also implicit that most animal production would have to be landless to achieve the level of agricultural intensification and residue recovery required.

Estimates in excess of 600EJ are extreme. The primary purpose of scenarios in this range is to provide a theoretical maximum upper bound and to illustrate the sensitivity of the models to key variables such as population, diet, and technological change. Estimates in this range are not intended to represent *socially acceptable* or *environmentally responsible* scenarios and none of the studies analysed here suggests that they are plausible.

Figure 2. Pre-requisites for increasing levels of biomass production



- Crop yields outpace demand: >2500Mha land for energy crops (includes >1300Mha good agricultural land)
- High or very high input farming, limited and landless animal production with dung recovery
- Low population (<9bn)
- Vegetarian diet OR extensive deforestation / conversion to managed forestry
- All residues a (<100EJ constrained use, not included in all studies)

- Crop yields outpace demand: >1500Mha land for energy crops (includes >1000Mha good agricultural land)
- Low population OR vegetarian diet OR extensive deforestation / conversion to managed forestry
- All residues a (<100EJ constrained use, not included in all studies)

- Crop yields keep pace with food demand: < 500Mha land for energy crops (mostly non-agricultural)
- Low population OR vegetarian diet OR limited deforestation.
- All residues a (<100EJ, constrained use, included in most studies)

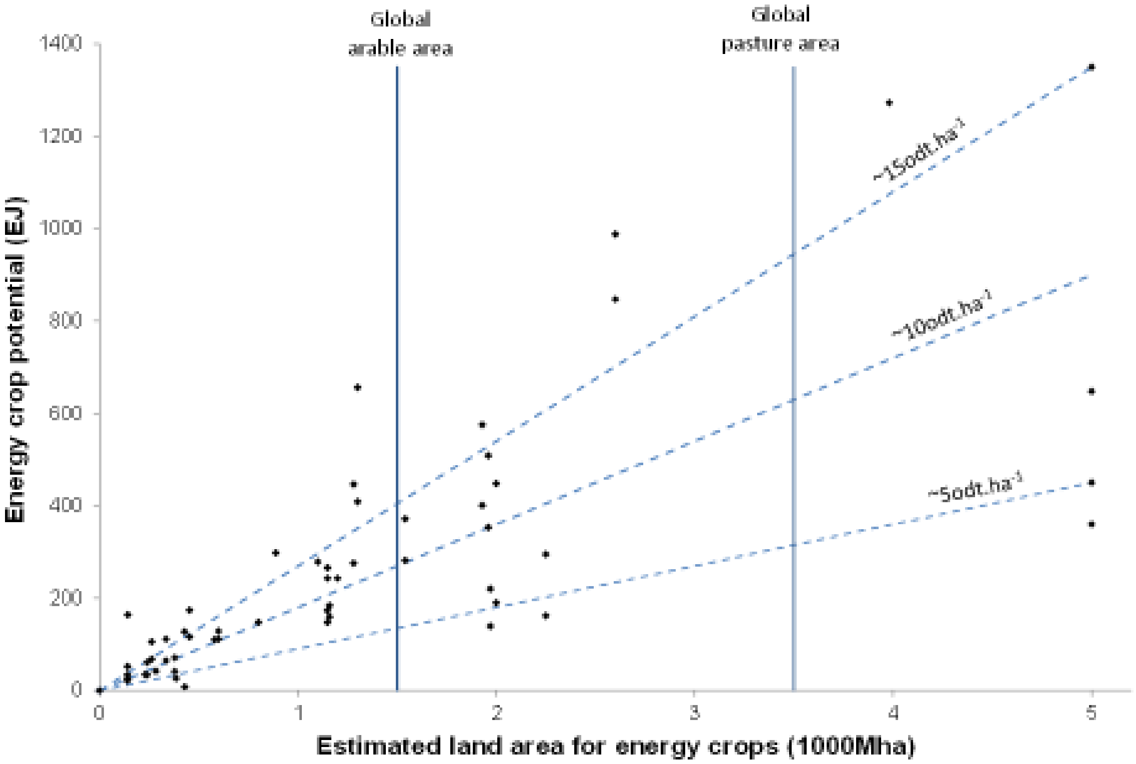
- Little or no agricultural land for energy crops, but up to <400Mha abandoned / degraded land
- High meat diet OR low input agriculture
- Limited expansion of cropland area AND high level of environmental protection
- Agricultural residues (<30EJ, not included in all studies)

[a] Agricultural residues, forestry residues, wastes: dung, municipal and industrial
[b] Global net primary terrestrial, above ground, productivity

The amount (and productivity) of land allocated to energy crops is one of the most important factors affecting bioenergy potential estimates. Figure 3 illustrates the striking differences between estimates for area and yield. Broadly speaking, the data points describing yields less than 5odt.ha^{-1} assume production on marginal and degraded land, whereas those describing yields in excess of 15odt.ha^{-1} assume both good quality land and technological advances to overcome biophysical constraints[43]. Those data points describing land areas in excess of 1000Mha assume that food crop yield growth will outpace demand leading to spare land for energy crops. Comparing the area of energy crops envisaged with the current global arable area (1500Mha) and pasture area (3500Mha) indicates the dramatic scale of the transition needed if energy crops were to make a major contribution to primary energy supply.

Most studies do not identify specific energy crop species and assume that the best adapted crop for each area and land type will be used. There is concern, however, that in studies where yield estimates derived from case-studies, sample plots and vegetation models are extrapolated to large areas of the planet's surface the resulting average yields may be unrealistically high[43,44]. Evidence that global net primary production (NPP) has been essentially unchanged over the last 30 years despite substantial investment in agriculture also suggests that technological advances may have limited impact on land productivity at a global scale[43,45,46].

Figure 3. The range of land area and yield estimates included in global energy crop scenarios



4. Cereal yields

All biomass potential studies assume that food demand will be met. How much land is needed is strongly influenced by yield projections for cereal crops. Cereals are of primary importance because about two thirds of all the energy in human diets is provided by just three crops: wheat, rice and maize[47] (~10% of the global land area). The main source of yield projections used in biomass studies to date is the FAO, and in particular two reports (published in 2003 and updated in 2006) that describe yield growth for the major cereal crops increasing more or less linearly at 0.9%pa to 2050 (0.9-1.4%pa between 1999-2030; 0.5-0.7%pa between 2030-50; cf. 1.6%pa for the period 1967-99). There is concern, however, that these projections may be over optimistic and give the impression that there is greater scope for productivity increases than is actually the case. The authors of ref.(21) identify that biologists tend to be among the most sceptical.

The FAO's analysis was undertaken before the 2007/8 commodity price spikes and one of the background assumptions in the 2003 report was that oil would cost less than 30 US dollars a barrel and decrease to 21 US dollars a barrel by 2015. In this scenario the cost of energy provides no constraint on agricultural production. Post 2007/8, concern about rapidly rising prices rekindled interest in food security and spawned a series of influential reviews examining whether increasing food yields could meet the demands of a growing population[48-54]. The FAO also updated their analysis concluding that cereal yield increases of 0.9%pa to 2050 remains possible, but only if sufficient investment is forthcoming[55]. The broad consensus of these reports was that it is likely to be technically possible to produce sufficient food to feed the 2050 global population, but there will be no room for complacency – particularly if the environmental impacts of global agriculture are also to be mitigated.

Yet these reports also highlight the inherent difficulties in undertaking a discussion about the world's capacity to produce sufficient food in abstract and aggregate terms. Digging beneath the surface of the analysis reveals that many of the underpinning assumptions are uncertain, in some cases contested, contingent on favourable investment scenarios and low energy prices, or subject to large regional variations. Rates of technological innovation and improvement are particularly problematic to anticipate as small changes make a big difference when compounded over multiple years in highly aggregate models. Focusing solely on the scope to increase food production also ignores issues such as post-harvest losses, food wastage, and inequities in distribution[56]. There are nevertheless some broad insights that might reasonably influence our interpretation of the bioenergy literature. Firstly, the green revolution led to food production outpacing demand but at a major cost to the environment, and with greatly increased energy, water and nutrient inputs [57]. Secondly, there is scope to increase yields and close the gap between what farmers currently get and what they might get with optimum agronomy, but many of the easy gains have already been achieved. The practicality of closing yield gaps is also hotly contested, varies dramatically by region, and depends as much on political and institutional factors as it does on fundamental agronomy and the availability of nutrient and water inputs. Thirdly, agricultural intensification is considered likely and necessary, but far from being a panacea it could further jeopardise the long term sustainability of food production unless combined with measures to conserve and maintain soil fertility.

A critical assumption embodied in many bioenergy models is that as agricultural yields increase, crop and pasture land will be spared from production and can be made available to grow energy crops. The reasoning is that as yields increase, prices drop and the agricultural area will decline. This causal chain assumes that demand for the products does not change and so the drop in price is sufficient to motivate land abandonment. If demand is elastic, however, prices may not change significantly. In this case the farmer has no incentive to abandon land, but may, conversely, be incentivised to increase the area they cultivate as this will directly lead to an increase in income[58]. Empirical studies undertaken at local and regional levels provide evidence of both land consuming and land sparing effects from intensification, but a lack of robust data on abandoned land, as well as the confounding effects of global trade and political intervention makes examining global level effect difficult[59,60]. Looking at changes in the global cultivated arable areas between 1970 and 2005, intensification only appears to be correlated with declines in cultivated areas between 1980-85 in the aftermath of a sustained decline in agricultural commodity prices and a steep rise in yields[58]. Moreover, explicit political intervention appears to have been an essential driver for cropland abandonment. There is some evidence that developing countries that increased staple crop yields most rapidly in the period 1979-99 had a slower deforestation rate than might otherwise have been the case[59], but the overall conclusion is that the link between crop intensification and land sparing is weak and uncertain. It follows that bioenergy estimates which are contingent on land sparing – i.e. those estimates in excess of ~300EJ – must be considered at least as uncertain, if not more so.

This discussion suggests that where bioenergy models are predicated on aggregate productivity projections for food crops they must be interpreted with great caution. Bioenergy models can identify the most important relationships, for example the relationship between increasing meat consumption and demand for land, but the outputs are essentially *"what if"* scenarios that possess no predictive capability and only hint at the level of effort that would be required to implement them. This is a striking contrast to the IEA's ebullience for 2035 and beyond.

5 Water scarcity

Globally, agriculture accounts for ~70% of all fresh water use, and scarcity is a growing concern[61]. The vast majority of this water is consumed during crop cultivation: either evaporated from the soil or transpired from plant leaves[61,62]. Yield and water transpiration are closely correlated and maximum crop growth only takes place when water availability is not restricted[63]. Crop growth models are able to predict water restricted yields for both food and energy crops, but competing demands on water supplies are not considered in depth in global bioenergy studies. A small number of irrigated energy crop scenarios have been developed for illustrative purposes, but the authors of these scenarios consider them unlikely to be sustainable[38],[19]. The vast majority of studies assume that energy crop production will be rain-fed. This assumption does not resolve the problem, however, as the concomitant intensification implicit for conventional agriculture also implies increased irrigation and water use[3].

Extending food and energy crop production onto marginal lands will require effort to increase water use efficiency (WUE) – the ratio of dry aboveground biomass to the amount of water evaporated and transpired. A variety of management options exist, for example, planting and harvesting operations can be timed to extend canopy closure and maintain ground cover in regions where soil evaporation is high[64]. Integrating perennial and annual crop production may also help increase productive crop transpiration and can improve water infiltration into the soil. Crop choice can also play a role, for instance the tropical (C4) grasses – maize, miscanthus, sugar cane – use less water than temperate (C3) crops such as wheat[65]. The potential for breeding individual crops to increase WUE, however, is less certain. Considering wheat as an example, other than changes in the harvest index there is limited evidence that WUE has improved as yields have increased[64]. Increasing drought tolerance by for instance reducing transpiration from leaves – would also restrict the level of carbon dioxide in the leaf and reduce the rate of photosynthesis.

Water availability remains a critical area for further research. There is a need for empirical evidence to support geo-hydrological models along with improved analysis at a regional level to better understand the constraints and opportunities[3,62]. Integrating food and energy crops is an option that might reduce water use in some locations[66], but the efficacy of these approaches needs to be proven, and, as with many other aspects of biomass production, effective management will be essential.

6 Sustainability assurance

Investment and effective governance are prerequisite to sustainable energy crop production. This, in turn requires a minimum level of regulatory competence and either a defined legal framework against which adherence can be monitored and enforced[38] or the widespread adoption of voluntary codes of practice that are demonstrably effective.

Investment will not occur unless energy crop production is economically viable. Studies exploring this aspect of production at a global scale extrapolate limited country specific data to obtain approximate global supply curves but the results are intrinsically hypothetical[20,26]. The main insight these studies provide is that the economics of biomass production will be highly sensitive to yield and land quality, giving biomass developers a strong incentive to identify productive, low cost land. This introduces a very possible scenario, where the option that stimulates greatest uptake of bioenergy, is not the same solution that gives best environmental protection globally or locally[33].

Land acquisition for bioenergy projects also has the potential to be highly contentious. Land availability estimates are underpinned by remote sensing approaches that are not able to identify who owns an area of land or who might be using it. Property rights can be highly complex and there may be major social risks in undertaking large scale projects[19,67]. The time taken to arrange access to land on an equitable basis may also be the rate limiting step for expanding energy crop production. The issue of land access and ownership is particularly acute when it comes to the potential use of marginal and degraded land. Grazing lands which are productive during the rainy season but look barren during the dry season are often classified as degraded[67]. These areas are often used extensively by the rural poor and may not be privately owned[38]. From an agronomy perspective, the growing conditions also tend to be difficult with low yields and high production costs[68,69].

The extent to which energy crops can deliver sustainable biomass on a global scale remains poorly understood. In the short term the best indication might come from an appraisal of past attempts to initiate large scale changes in global agriculture. Attempts to close yield gaps, implement sustainable agriculture, limit deforestation, stimulate rural development, and implement environmental stewardship might all reasonably be examined, as might the growing effort to implement biomass sustainability standards and certification in existing supply chains. In the longer term there is a need to monitor attempts to stimulate biomass supply, gather empirical evidence about what works, and demonstrate best practice.

5. Learning by doing

Moving to a future where biomass supplies a significant proportion of global energy demand would require large scale and systemic change. Global biomass potential studies provide a lens through which such system level changes can be examined. They are important because they define the context in which governments and international organisations debate the future role of bioenergy and decide policies designed to increase deployment.

Yet biomass potential studies provide limited insight into the level of deployment that might be achievable in practice. Rather, they describe scenarios in which biomass makes an increasing contribution to primary energy supply while attempting to minimise the negative impacts by imposing environmental constraints on deployment. They are systematically optimistic in the sense that they try to describe sustainable paths as opposed to unsustainable ones. What they are *not* are forecasts extrapolated from empirical observations or any practical experience of trying to achieve large scale transitions in crop production, or residue use at a global scale. This is not always apparent from the way in which modelling results are interpreted and described.

One of the criticisms levied at biomass potential assessments has been the lack of standardised and consistent methodologies. Our analysis suggests the range of estimates is driven more by the choice of alternative assumptions than methodological differences. One area where harmonisation would be valuable, however, is the use of descriptive terms that are precise but not value laden. Terms such as *abandoned land* and *surplus forestry* are prone to misinterpretation and should be avoided.

Energy crops are the most important component in the majority of global biomass assessments. Some of the trade-offs that would be required to make space for these crops go against existing global trends: for instance, the trend for increasing meat consumption as incomes rise. Others, like the public acceptability of land-use change, are controversial. Many more, for example the implications of large scale energy crop production on water availability and the consequential impacts on food supply, remain poorly understood. The implication for policymakers is that decisions about how to pursue bioenergy must be made in the face of inherent uncertainty.

Yet many of the important open questions will only be resolved as incremental attempts are made to initiate energy crop production and increase the role of biomass in global energy supply. Focussing on near term opportunities could help identify the merits and pitfalls of expanding biomass deployment and lead to an improved understanding of the level of effort involved in going to higher levels of biomass use. Such a bottom-up approach could also better inform the policy debate.

The opportunity to experiment and to gather empirical evidence should also not be overlooked. Provided that soils are not degraded or biodiversity destroyed, many investments in bioenergy are ultimately reversible. As the first few exajoules of energy crops are deployed, the claimed benefits of integrated food and biomass production could be evaluated at scale, as could the feasibility and sustainability benefits of extending energy crop production onto marginal, degraded and deforested land. Given that effective governance is considered a pre-requisite for sustainable implementation, there is also an opportunity to monitor the efficacy of regulatory approaches such as biomass sustainability certification and use this real world experience to inform projections of what might be possible in the future. Bioenergy is likely to remain controversial, but focussing on practical next steps could lay the foundations of a sustainable bioenergy sector, however large it proves to be in the future.

Supplementary Information: is available in the online version of the paper.

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The Global Bioenergy Resource

Dr Raphael Slade[†], Dr Ausilio Bauen[†], Dr Robert Gross[†]

Supplementary Tables

Table S1: Global biomass potential estimates, <100EJ

(Reference) Lead author-year	Total Potential	Energy crops		Residues			Forestry	Population
				AR	FR	W		
	EJ	Mha	EJ / [$\text{odt.ha}^{-1}.\text{yr}^{-1}$]	EJ	EJ	EJ	EJ	billion
(22) Field-08	27	386	27 [3.5]					ns
	2000-30 scenario. Existing abandoned cropland only. Spatially explicit methodology.							
(34) Sims-06	22-34	141	22-34 [4-12]					
	2000-30 scenario. Total is summation of a rule based inventory.							
(18) Bauen-04	60	283	42.5 [~8]	---------------17.5-----------				ns
	2000-30 scenario. Total is summation of a rule based inventory							
(31) Moreira-06	164	143	164 [~60]					ns
	2000-30 scenario. Sugar cane in tropics – very high yields anticipated (~double world average) due to technology driven yield increases.							
(28) Hoogwijk-03 (scenario-1)	33	430	8 [1]	32 Net 25EJ when demand for biomaterials excluded	60	16	Exc.	8.7 – 11.3
	2050 scenario. Optimistic recovery of residues. Energy crops on degraded land only. 'Moderate' or 'Affluent' Diet. Low external input agriculture. 'Safety factor of two' on land available for food.							
(21) Erb-09 (scenario-1)	58/91	>200/ >300[a]	28 / 63	30 / 28			Exc.	9.16
	2050 scenario: 'Western diet' (high calorie, meat and animal products) / 'Current trend diet' (moderate increase in calories and meat). Cropland expansion into grazing land:19% / 9% . Yield assumes 100% of above ground NPP. Intensive livestock production. Rapid yield increases in line with FAO 2003.							
(21) Erb-09 (scenario-2)	105/128	>300[a]	77 / 100	28 / 28			Exc.	9.16
	2050 scenario. Cropland expansion into grazing land: 19% / 9% . Low meat (humane livestock) / very low meat diet (organic livestock). Yield assumes 100% of above ground NPP harvested. Reduction in sugar, meat and fat consumption by 30% in wealthy countries. Moderate yield increases (<FAO 2003)							
(14) Thrän-10 (scenario-1)	16		16				Exc.	8.3Bn
	2050 'sustainable land use' scenario. No conversion of forests or grassland to cropland. 3 – 8% pa conversion of fallow land. 75% of fallow land (formerly arable) used to produce hay, SRC, and silage in 2050. No constraint on diets. Constant food crop yield improvement at 1.46%pa							
(14) Thrän-10 (scenario-2)	39		39				Exc.	8.3Bn
	2050 'environment and health scenario'. No conversion of forests or grassland to cropland. 3-8% pa conversion of fallow land. 75% of fallow land (formerly arable) used to produce hay, SRC, and silage in 2050. 30% reduction in food consumption in US, Canada, EU and Australia							

[†]Centre for Energy Policy & Technology, Imperial College London, 14 Princes Gardens London, 14 Princes Gardens, South Kensington, London, SW7 1NA

	by 2050 (convergence to WHO target) Doubling of organic production every 10 years. Declining yield improvement rate from 1.46% pa in 2010 to 1.02%pa in 2050.				
(14) Thrän-10 (scenario-3)	96		96	Inc.	8.3
	2050 ‘business as usual’ scenario. Expansion onto ‘grazing’ and ‘deforested’ land. Deforestation (0.24%pa) and grassland conversion (0.1%pa) permitted. No constraint on diet. Constant food crop yield improvement rate: 1.46% pa. No organic production.				
(38) WGBU-09 (scenario-1)	34/61	240	34/61 [7.5(rain fed) / 10.8 (10% irrigated)]	0	ns
	2050 scenario. ‘high farmland’ / ‘high nature conserving’ scenarios. Competition for water not considered for irrigated scenario. Needs 125% of current farmland in 2050				
(38) WGBU-09 (scenario-2)	42/71	380	42/71 [9.2(rain fed) /12.6(10% irrigated)]	0	ns
	2050 scenario. ‘high farmland’ / ‘low nature conserving’ scenarios. Competition for water not considered for irrigated scenario. Needs 125% of current farmland in 2050				

Abbreviations – EC: energy crops; AR: Agricultural residues; FR forestry residues; F: forestry; W: wastes; SRC: short rotation coppice; ns: not specified; Inc.: included; Exc.: excluded

Descriptions – adjectives used to describe scenarios and land classifications (e.g. ‘abandoned land’, ‘rest land’, etc.) are those reported in each individual study and may not be directly comparable between studies by different authors.

[a] Indicative only as for this study yield varies with location – estimated here assuming an average yield of 10odt.$ha^{-1}.yr^{-1}$

Table S2: Global biomass potential estimates, 100-300EJ

(Reference) Lead author-year	Total Potential	Energy crops		Residues (EJ)			Forestry	Population
				AR	FR	W		
	EJ	Mha	EJ [odt.$ha^{-1}.yr^{-1}$]	EJ	EJ	EJ	EJ	billion
(19) Beringer-11	126-216 / 152-274	142-454	26-116 / 52-174 [~10-14 / 18-21]	-------------100------------			Up to 135Mha deforestation	ns
	2050, rain fed / 10% irrigated scenario. 70% increase in food production will be required. Either limited expansion in area for food (120Mha) OR food crop yield increases have to be stabilized at ~ 1.2% per year. No existing pasture or cropland conversion to energy crops. High level of environmental protection, but expansion onto natural grasslands and forestry permitted.							
(24) Haberl-10	160-270	ns	44-133	49	19-35	50		ns
	2050 scenario. Analysis of residues relies on extensive extrapolation.							
(30) Johansson-93	205	429	128 [10]	25	3	39	10	ns
	2050 scenario. Rule based approach.. focuses on ‘degraded land’ in developing countries and ‘excess agricultural land’ in developed countries							
(33) Rokityanskiy-06	175-230	500-610					175-230 Models above ground NPP	Follows IPCC SRES A1
	2100 scenario. Model constrained to allow ‘adequate area for food production’, but assumptions not explicit. Area is net avoided deforestation and afforestation under exponentially increasing carbon price scenarios – 70% of which is located in Africa and South America. Yields assumes							

	above ground NPP: average ~20odt.ha^{-1}. Relationship between avoided deforestation and energy production not explicit.							
(39) Yamomoto-01	182/136	~396/~79 [b]	110/22 [15]	----------72/114----------			25% decrease in mature forest area [a]	9.6 / 11
	2050/2100 scenarios. Food crop yield increases defined for each region: yield in 2100 ranges between 1x and 3x yields in 1990. Developing country GDP converges to developed region GDP. Demand for food rises faster than crop yield improvements, therefore bioenergy potential decreases between 2050 and 2100							
(40) Yamomoto-99	426	~540	149 [15]	-------------277-----------			80% decrease in mature forest area [a]	10bn in 2050 rising to 11.6bn in 2100
	2100 scenario. Food crop yields increase 1.77x yields in 1990 in developed world and 2.49x yields in 1990 in developing world by 2100. Assumes no constraints on residue recoverability							
(41) Yamomoto-00	221-310	~219-540	61-150 [15]	-----------160-186--------			No change	10bn in 2050 rising to 11.6bn in 2100
	2100 scenario. Food crop yields increase 1.77x yields in 1990 in developed world and 2.49x yields in 1990 in developing world by 2100. Assumes no constraints on residue recoverability							

Abbreviations – EC: energy crops; AR: Agricultural residues; FR forestry residues; F: forestry; W: wastes; SRC: short rotation coppice; ns: not specified; Inc.: included; Exc.: excluded

Descriptions – adjectives used to describe scenarios and land classifications (e.g. ‘abandoned land’, ‘rest land’, etc.) are those reported in each individual study and may not be directly comparable between studies by different authors.

[a] Total forest area does not decrease, but mature forest is used to supply round-wood and replaced with growing forest.

[b] It is assumed that up to 619Mha of land for arable and / or energy crops can be obtained from converting fallow, degraded and semi-desert land. The figures shown here are calculated from the energy and yield figures provided in the paper.

Table S3: Global biomass potential estimates, 300-600EJ

(Reference) Lead author-year	Total Potential	Energy crops		Residues (EJ)			Forestry	Population
				AR	FR	W		
	EJ	Mha	EJ [odt.ha^{-1}.yr^{-1}]	EJ	EJ	EJ	EJ	billion
(23) Fischer-01	370-450	1970	140/220 [~3.8-4.8]	20		120	90-110	>10
	2050 scenario. 180Mha additional arable area from forests and grasslands. 1.1%pa yield increase in food crop yields and 1%pa yield increase in energy crop yields. All global forest is managed for energy purposes where accessible (3870Mha; ~0.8-0.25%pa yield increase). 60-75% of global grassland area including pasture is dedicated to energy crops. Source of yield increases unclear as production is assumed to be rainfed.							
(16) Lysen-08	290-530	>1000 abandoned agricultural >1000	120 abandoned agricultural 70 degraded	-----------40/100---------			60/100	9.4

		degraded land	140 technological learning		
	2050 scenario. ‘Moderate’ GDP growth at 2%pa. Diet not specified. Crop yields increase at 1.4%pa [c]. Large scale conversion of land. Rapid increases in food and energy crop yields. Similar approach to Hoogwijk05.				
(27) Hookwijk-05 (scenario-1)	311/395	600/1200 abandoned agricultural ~1150 rest land	129/243 [~11 [b]] abandoned agricultural 9/4 [<3[b]] low productivity land 173/148 [~8 [b]] rest land	Large scale deforestation	11.3/15.1bn
	IPCC SRES A2-2050 /A2-2100 scenarios. High meat consumption. Food crop yields increase up to 78% of optimal productivity for each land type by 2050 (increasing to 86% of optimal productivity by2100). Energy crop yields improve at 1.2%pa, up to max1.1x 1995 optimal productivity for each land type. Large scale deforestation to keep pace with food demand (~700Mha deforestation).				
(27) Hookwijk-05 (scenario-2)	322/485	~1100/2000 abandoned agricultural 230 rest land [a]	279/448 [~13 [b]] abandoned agricultural 8/5 [<3 [b]] low productivity land 35/32 rest land [~8]	0	9.4/10.4
	IPCC B2-2050 /B2-2100 scenarios. Food crop yields increase up to 78% of optimal productivity for each land type by 2050 (increasing to 89% of optimal productivity by2100). Low meat consumption, low biomass supply. Energy crop yields improve 1.2%pa, up to max1.1x 1995 optimal productivity for each land type.				
(27) Hookwijk-05 (scenario-3)	699	~1300 abandoned agricultural 230 rest land [a]	656 [~13 [b]] abandoned agricultural 39 [~8 [b]] rest land	0	8.7 in 2050 decreasing to 7.1 in 2100.
	IPCC SRES B1-2050 scenario. Low meat diet. Food crop yields increase up to 82% of optimal productivity for each land type by 2050 (89% by2100). High technology, high fertiliser use. Implicit requirement for increased irrigation to deliver increase in food yields. High food trade levels. 1.6%pa yield improvement in energy crops up to max 1.3x 1995 optimal productivity. ~10% of ‘rest land’ used for energy crops.				
(20) de Vries-07	401-575 / 160-184 / 353-509 / 282-372	1930/1160 / 1960 / 1540	401-575 / 160-184 / 353-509 / 282-372	0	Same as Hoogwijk05 (IPCC SRES)

	IPCC SRES A1/ A2 / B1 / B2 2050 scenarios. Yield improvements up to 1.3-1.5 x optimal yield in 2000. Use of 'rest land' limited to ~20% in all scenarios.							
(36) WEA-00	276-446	1280	276-446 [8-5-15]					ns
	Simple inventory estimate. Includes traditional biomass							
(37) Wolf-03 (scenario-1)	360	5000	360 [4]				Inc.	~9
	2050 scenario. Vegetarian diet and ' best achievable food crops yields' with low external inputs (fertilizer) OR Affluent diet and best achievable food crops yields with high external inputs. Low energy crop yield scenarios results in to large scale deforestation as agriculture is extended onto forest areas and grassland							
(37) Wolf-03 e (scenario-2)	295/162	2250	295/162 [7.3 / 4]				Exc.	~9
	2050 scenario with high/low inputs to energy crop production. Affluent diet. Best achievable food crop yields with high external inputs.							

Abbreviations – EC: energy crops; AR: Agricultural residues; FR forestry residues; F: forestry; W: wastes; SRC: short rotation coppice; ns: not specified; Inc.: included; Exc.: excluded

Descriptions – adjectives used to describe scenarios and land classifications (e.g. 'abandoned land', 'rest land', etc.) are those reported in each individual study and may not be directly comparable between studies by different authors.

[a] Rest land includes: savannah, extensive grassland, and shrubland. The proportion of this area used for energy crops is not entirely clear, but appears to be 1150Mha (50% of total area) in the A1 scenario and 230Mha (10% of total area) in the B1

[b] Yields are calculated in the IMAGE model according to land class and area, the figure shown here is the global average

[c] This figure is not stated explicitly in the paper but is the global average figure from the quoted reference: (Bruinsma2002)

[d] As primary energy

[e] Strictly speaking these data points fits within the 100-300EJ band, but the assumptions – particularly that food crop yield increases release agricultural land for energy crops means that it has more in common with the estimates in the 300-600EJ band.

Table S4: Global biomass potential estimates, >600EJ

Reference Lead author-year	Total Potential	Energy crops		Residues (EJ)			Forestry	Population
				AR	FR	W		
	EJ	Mha	EJ [odt.ha^{-1}.yr^{-1}]	EJ	EJ	EJ	EJ	billion
(28) Hookwijk-03 (scenario-2)	1130	2600 agricultural land 580 degraded land	988 [20] agricultural land 110[10] degraded land	10	10	12	0	8.7
	2050 scenario. 'High External Input' farming. Moderate meat diet. Best technical production means with only limit being water availability. Safety factor of two on the land required for food. Comparatively high yield assumptions for energy crops. Assumes very high food crop yields – double world average							
(37) Wolf-03	648	5000	648 [7.3]				Inc.	7.7

(scenario-3)								
	2050 scenario. High input system using all available resources, technologies and management. Largely vegetarian diet requiring ~30% of land required for affluent diet. Safety factor of two on the land required for food. Moderate energy crop yield but still requiring fertilisation. Large scale deforestation as agriculture is extended onto forest areas and grassland.							
(35) Smeets-07	1548	3700 surplus pasture 284 wood plantation	1272 [18] surplus pasture	66 net	8	22	180 net	8.8
	2050 scenario. Estimate exceeds current terrestrial, above-ground NPP. No safety margin on land use for food. Very high intensity farming with 'landless' (industrialised) animal production. High feed conversion yield from vegetation to animal mass. All available food crop production technology and irrigation included where possible. Crop yields increased 4.6x by 2050. Food consumption per capita is 1.2x 1998 value. Assumes total global annual forest growth increment is harvested where accessible. Study illustrates a hypothetical scenario where all model parameters are set at the maximum conceivable level.							
(27) Hookwijk-05 (scenario-4)	657 / 1115	~1300 / ~2600 abandoned agricultural ~1150 rest land [a]	409/847 [~17] abandoned agricultural land 5/2 [<3] low productivity land 243/266 [~11] rest land				Exc.	8.7 in 2050 decreasing to 7.1 in 2100.
	IPCC A1-2050 /A1-2100 scenarios. Food crop yields increase up to 82% of optimal productivity for each land type by 2050 (increasing to 89% of optimal productivity by2100). High meat diet. Implicit requirement for high technology and high fertiliser use. Energy crop yields improve 1.6%pa up to maximum 1.5x 1995 level (i.e. yield gap closes plus technical advances). Massive land use change: ~50% of "rest land" used for energy crops. Study illustrates sensitivity of results to compounding yield projections for long periods.							
(2727) Hookwijk-05 (scenario-5)	699	~2600 abandoned agricultural land 230 (rest land [a])	656 [~13] abandoned agricultural land 5/2 [<3] low productivity land 39[~9] rest land				Exc.	8.7 in 2050 decreasing to 7.1 in 2100.
	IPCC B1-2100 scenario. Food crop yields increase up to 82% of optimal productivity for each land type by 2050 (89% by2100). Implicit requirement for high technology and high fertiliser use. Low meat diet. Energy crop yields improve 1.6%pa up to maximum 1.3x 1995 level. ~10% of 'restland' used for energy crops.							

Abbreviations – EC: energy crops; AR: Agricultural residues; FR forestry residues; F: forestry; W: wastes; SRC: short rotation coppice; ns: not specified; Inc.: included; Exc.: excluded

Descriptions – adjectives used to describe scenarios and land classifications (e.g. 'abandoned land', 'rest land', etc.) are those reported in each individual study and may not be directly comparable between studies by different authors.

[a] Rest land includes: savannah, extensive grassland, and shrubland. The proportion of this area used for energy crops is not entirely clear, but appears to be 1150Mha (50% of total area) in the A1 scenario and 230Mha (10% of total area) in the B1 scenario.

[†] Centre for Energy Policy & Technology, Imperial College London, 14 Princes Gardens London, 14 Princes Gardens, South Kensington, London, SW7 1NA