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Global bioenergy resources

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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, particularly 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 that there is a disjunct between the evidence that global bioenergy studies can provide and policymakers' 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 to better inform the policy debate.

The large-scale production of renewable heat, electricity and transport fuel from biomass is an important component in many climate change mitigation and energy supply scenarios[1–4]. The International Energy Agency, for example, estimates that biomass could contribute an additional 50 EJ (~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 incentivize 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 interlinks 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 standardized assessment methodologies confuses policymakers, 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 realized.

Here, we analyse how scenarios for increasing bioenergy deployment are contingent on anticipated demand for food, energy and environmental protection, and expectations for 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 past 20 years. The technical and sustainability assumptions that lie behind these estimates are exposed and their influence on calculations of potential is described.

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, are invariably based on more challenging assumptions, which would be more difficult to implement in practice.

The most controversial and influential assumptions relate to the future role of energy crops. We examine these assumptions, focusing 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, and recommend adopting a learning-by-doing approach to testing the feasibility and sustainability impact of increasing bioenergy deployment.

Estimating the global biomass resource

The global availability of biomass 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 Organization'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 that allow several 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 ready supply 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 affected 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 normalized 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 18 GJ per oven dry tonne (odt)) and the chief technical and environmental assumptions on which they are predicated.

Our systematic review identified 90 studies. Of these, 28 contained original analyses describing over 120 estimates for the future contribution of biomass to global energy supply[1,14,16–41]. Most of these estimates are for 2050, reflecting the importance of this date in much of the modelling and scenario analyses that have 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).

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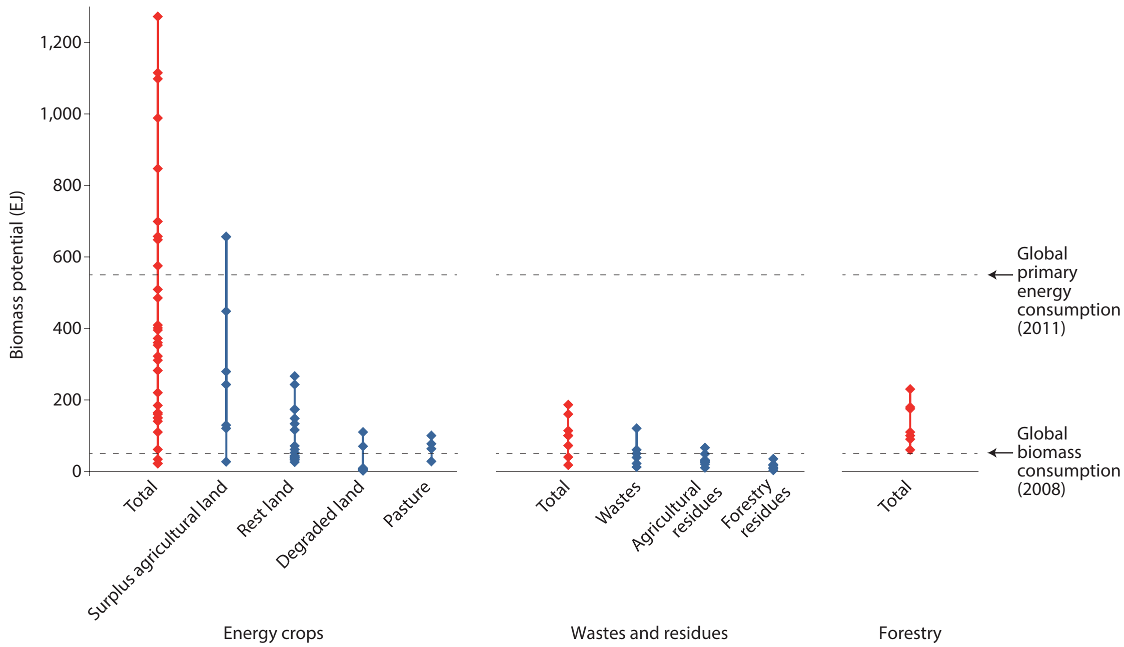

Figure 1 | Estimates for the contribution of energy crops, wastes and forest biomass to future energy supply. Vertical lines show the range of estimates for each resource category and diamonds indicate the results of individual studies (estimates include unconstrained values). Surplus agricultural land 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, and is a highly aggregate category defined by the FAO as areas spanning more than 0.5 ha with trees taller than 5 m. Some studies make further distinctions between primary forests and plantations.

The most important potential sources of biomass are energy crops (22–1,272 EJ), agricultural residues (10–66 EJ), forestry residues (3–35 EJ), wastes (12–120 EJ) and forestry (60–230 EJ), summarized in Fig. 1. Not all studies include all of these categories in their analysis — in particular, many authors exclude biomass extraction from primary forests because they consider that the risk of adverse impacts on biodiversity and carbon stocks is too great. By way of comparison, the total human appropriation of net terrestrial primary production (including the entirety of global agriculture and commercial forestry) is around 320 EJ, of which 220 EJ is consumed and 100 EJ discarded as residues or otherwise destroyed during harvest[42]. This is considerably less than the current global primary energy supply (~550 EJ).

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 summarized in Fig. 2.

Estimates up to ~100 EJ (around one-fifth 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 (8–71 EJ, ~140–400 Mha) predominantly comes from agricultural land identified as abandoned, degraded or deforested, and from limited expansion of energy crops onto pasture. The input from wastes and residues is considered in only a few studies, but where included the net contribution is in the range of 17–30 EJ. Most of these studies in exclude biomass extraction from non-commercial forestry.

Estimates falling within the 100–300 EJ range (roughly half of 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 (100–500 Mha) yielding 10–20 odt 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. Most estimates in this range also rely on a larger contribution from residues and wastes (60–120 EJ). 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 the recoverability of such wastes and residues.

Estimates in excess of 300 EJ and up to 600 EJ (600 EJ is slightly more than current global primary energy supply) are all based 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 (>1,000 Mha) could be made available for energy crops. In addition, these estimates assume that an area of grassland and marginal land larger than India (>500 Mha) 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 by extensive deforestation. It is also implicit that most animal production would have to be landless (for example, industrial cattle feedlots and poultry farms) to achieve the level of agricultural intensification and residue recovery required.

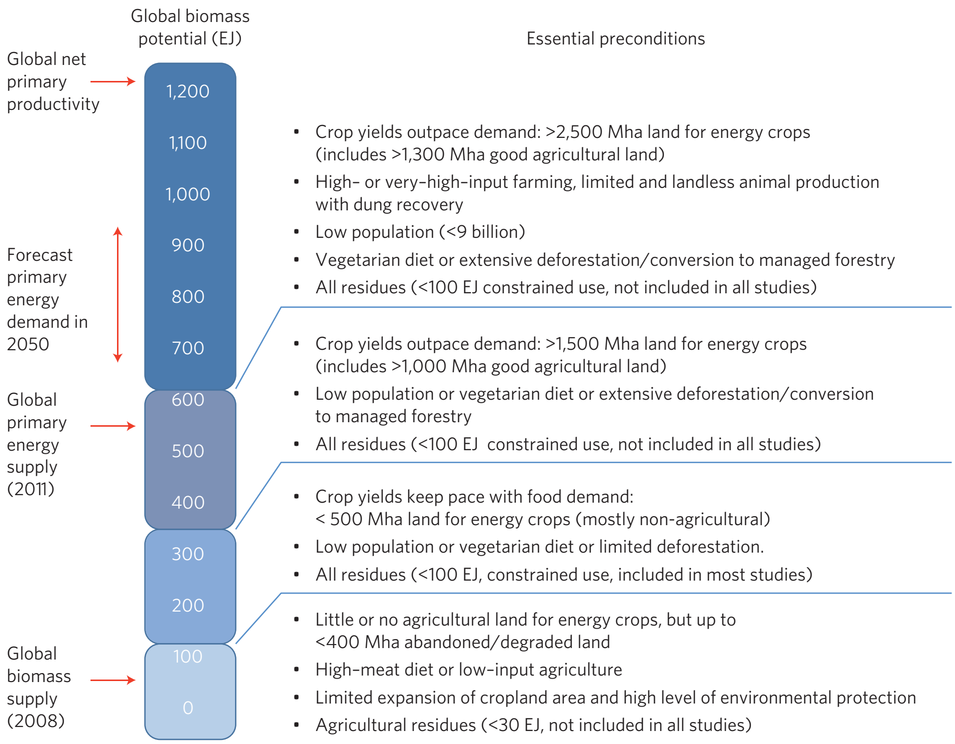

Figure 2 | Essential preconditions for increasing levels of biomass production. In each band the minimum essential assumptions that must be included in global biomass models to achieve the given range of biomass potential are indicated. 'All residues' includes: wastes (dung, municipal and industrial), agricultural residues and forestry residues. Indicated global net primary productivity is aboveground terrestrial productivity only. Figure reproduced with permission from ref. 13, © 2011 Raphael Slade.

Estimates in excess of 600 EJ 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. They are not intended to represent socially acceptable or environmentally responsible scenarios, and none of the studies analysed here suggests that they are plausible.

The amount (and productivity) of land allocated to energy crops is one of the most important factors affecting estimates of bioenergy potential — Fig. 3 illustrates the striking differences between those for area and yield. Broadly speaking, the data points describing yields less than 5 odt ha^{-1} assume production on marginal and degraded land, whereas those describing yields in excess of 15 odt ha^{-1} assume both good quality land and technological advances to overcome biophysical constraints[43]. Data points describing land areas in excess of 1,000 Mha assume that yield increases in food crops will outpace demand, leading to spare land for energy crops. Comparing the predicted area of energy crops with the current global arable area (1,500 Mha) and pasture area (3,500 Mha) 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 the resulting average yields may be unrealistically high in studies where yield estimates derived from case-studies, sample plots and vegetation models are extrapolated to large areas of the planet's surface[43,44]. Evidence that global net primary production (NPP) has remained essentially unchanged over the last 30 years despite substantial investment in agriculture also suggests that technological advances may have a limited impact on land productivity at a global scale[43,45,46].

Cereal yields

All studies of biomass potential 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] — which together already occupy 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)[48,49] that describe yield growth for the major cereal crops increasing more or less linearly at 0.9% per year to 2050 (0.9–1.4% per year between 1999–2030; 0.5–0.7% per year between 2030–2050; compared with 1.6% per year for the period 1967–1999). 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. Erb *et al.* identify that biologists tend to be among the most sceptical[21].

The FAO's analysis was undertaken before the 2007/2008 commodity price spikes and one of the background assumptions in the 2003 report was that oil would cost less than US$30 per barrel and decrease to US$21 per barrel by 2015. In this scenario the cost of energy provides no constraint on agricultural production. Post 2007/2008, 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[50–56]. The FAO also updated their analysis, concluding that cereal yield increases of 0.9% per year to 2050 remain possible, but only if sufficient investment is forthcoming[57]. 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.

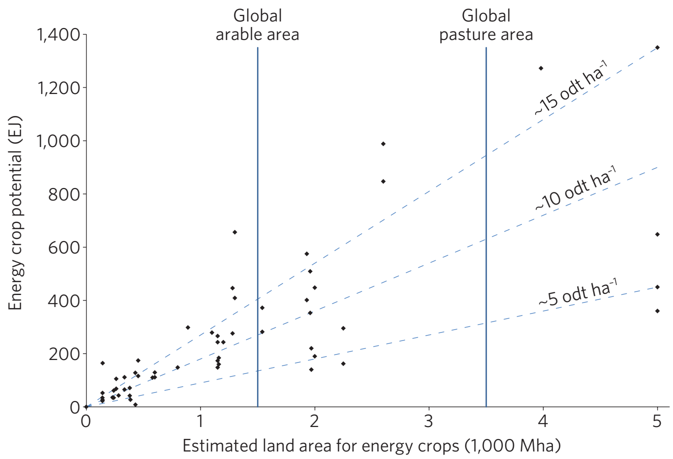

Figure 3 | The range of yield and land area estimates included in global energy crop scenarios. Diamonds indicate estimates taken from individual studies. Dashed lines show how energy crop potential would vary with planted area, assuming a constant yield between 5–15 odt ha^{-1}.

Yet these studies 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 these analyses indicates 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 several 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[58]. There are nevertheless some broad insights that might reasonably influence our interpretation of the bioenergy literature. First, 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[59]. Second, there is an opportunity to increase yields and close the gap between what farmers now 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. Third, agricultural intensification is considered probable and necessary, but far from being a panacea it could further jeopardize 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 for growing 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 incentivized to increase the area they cultivate as this will directly lead to an increase in income[60]. 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[61,62]. Looking at changes in the global cultivated arable areas between 1970 and 2005, intensification only seems to be correlated with declines in cultivated areas between 1980–1985 in the aftermath of a sustained decline in agricultural commodity prices and a steep rise in yields[60]. Moreover, explicit political intervention seems to have been an essential driver for cropland abandonment. There is some evidence that the developing countries that increased staple crop yields most rapidly in the period 1979–1999 had a slower deforestation rate than might otherwise have been the case[61], but the overall conclusion is that the link between crop intensification and land sparing is weak and uncertain. It follows that bioenergy estimates that are contingent on land sparing — that is, those estimates in excess of ~300 EJ — must be considered at least as uncertain, if not more so.

This discussion suggests that where bioenergy models are based 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 link 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 International Energy Agency's high expectations for an additional 50 EJ contribution to primary energy by 2035.

Water scarcity

Globally, agriculture accounts for ~70% of all fresh-water use, and scarcity is a growing concern[63]. The vast majority of this water is consumed during crop cultivation: either evaporated from the soil or transpired from plant leaves[63,64]. Yield and water transpiration are closely correlated and maximum crop growth only takes place when water availability is not restricted[65]. 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 few irrigated energy crop scenarios have been developed for illustrative purposes, however the authors consider them unlikely to be sustainable[38,19]. Most studies assume that energy crop production will be rain-fed. This 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 efforts 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[66]. Integrating perennial and annual crop production may also help to 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[67]. 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[66]. 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[3,64]. Integrating food and energy crops is an option that might reduce water use in some locations[68], but the efficacy of these approaches needs to be proven, and, as with many other aspects of biomass production, effective management will be essential.

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 in which 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[19,69]. 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 that are productive during the rainy season but look barren during the dry season are often classified as degraded[69]. 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[70,71].

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. Efforts 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.

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-wide changes can be examined. They are important because they define the context in which governments and international organizations 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 minimize 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 standardized and consistent methodologies. Our analysis suggests that the range of estimates is driven more by the choice of alternative assumptions than methodological differences. One area where harmonization 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 most 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 trade-offs, 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. Focusing on near-term opportunities could help to 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 large-scale integrated food and biomass production could be evaluated, 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 prerequisite for sustainable implementation, there is also a chance 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 focusing on practical next steps could lay the foundations of a sustainable bioenergy sector, however large it proves to be in the future.

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Author contributions

R.S. Designed and planned the work, undertook the analysis and wrote the manuscript. A.B. and R.G. contributed to the design, drafting and review.

Additional information

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Competing financial interests

The authors declare no competing financial interests.