Energy from biomass: the size of the global resource

An assessment of the evidence that biomass can make a major contribution to future global energy supply

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A report produced by the Imperial College Centre for Energy Policy and Technology for the Technology and Policy Assessment Function of the UK Energy Research Centre

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Preface

This report was produced by the Technology and Policy Assessment (TPA) function of the UK Energy Research Centre.

The TPA was set up to address key controversies in the energy field. It aims to provide authoritative and accessible reports that set very high standards for rigour and transparency. The subject of this report was chosen after extensive consultation with energy sector stakeholders and upon the recommendation of the TPA Advisory Group, which comprises independent experts from government, academia and the private sector.

The primary objective of the TPA, and this report, is to provide a thorough review of the current state of knowledge. New research, such as modelling or primary data gathering may be incorporated when essential. The ambition is to explain the findings of the review in a way that is accessible to non-technical readers and is useful to policy makers.

The TPA research protocols are based upon best practice in evidence based policy. An extensive and systematic search for reports and papers was undertaken. Experts and stakeholders were also invited to comment and contribute through the forum of an Expert Group. The project scoping note and related materials are available from the UKERC website: www.ukerc.ac.uk.

About UKERC

The UK Energy Research Centre carries out world-class research into sustainable energy systems. It is the hub of UK energy research and the gateway between the UK and international energy research communities. Its interdisciplinary, whole-systems research informs UK policy development and research strategy.

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The above individuals represent a range of views on global biomass potentials and none are responsible for the content of this report.

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Executive summary

Why this report?

Many future energy scenarios indicate a prominent role for bio-energy (fuels, heat and power from biological matter or *biomass*), but there is significant controversy around the potential contribution of biomass to global energy production. This stems from the environmental and social risks that could be associated with producing biomass. Concerns include the sustainability of increasing crop yields and intensifying agriculture, the prospect that competition for land will impact on food production, and the potential for environmentally damaging land use change. The controversy surrounding sustainable biomass supply feeds further controversy related to the long term role of bio-energy and the appropriateness of policies to promote its utilisation and development.

This report aims to support informed debate about the amount of biomass that might be available globally for energy, taking account of sustainability concerns. It uses a systematic review methodology to identify and discuss estimates of the global potential for biomass that have been published over the last 20 years. The assumptions – both technical and ethical – that lie behind these are exposed and their influence on calculations of biomass potential described.

The report does not seek to determine what an acceptable level of biomass production might be. What it does is reveal how different levels of deployment necessitate assumptions that could have far reaching consequences for global agriculture, forestry and land use; ranging from a negligible impact to a radical reconfiguration of current practice. The report also examines the insights the literature provides into the *interactions* between biomass production, conventional agriculture, land use, and forestry.

Sources of biomass and sources of controversy

Biomass for energy may be obtained from a diverse range of sources, the most important of which are energy crops, agricultural and forestry residues, wastes, and existing forestry. By far the widest range of potentials relate to energy crops, since estimates of their contribution can range from very small to beyond current global primary energy supply. Because these crops require land and water, they also stimulate the most discussion about whether deployment at scale could be beneficial – e.g. mitigating some of the environmental damage caused by conventional agriculture; or detrimental – e.g. increasing competition for land, contributing to food price increases and damaging ecosystems. The other categories of biomass – agricultural and forestry residues, wastes and existing forestry – are comparatively neglected in global studies but could make a contribution comparable in size to the existing use of biomass for energy (around 10% of global primary energy supply). Practical and environmental constraints will limit the use of agricultural and forestry residues.

Methodologies, data sources and issues in defining biomass potential

The methodologies used to estimate global biomass potentials, and energy crop potentials in particular, have evolved over the last 20 years. The earlier studies used simple assumptions about the area of land that could be dedicated to energy crops and the quantity of residues that could be extracted from agriculture and forestry. Recent innovations include using spatially explicit modelling techniques and scenarios.

All global level assessments, whether for biomass or food, face data constraints. All studies rely upon datasets collated by the Food and Agriculture Organisation (FAO). Whilst the data are excellent for some regions, there is a paucity of robust, reliable and high resolution data for important global regions such as Africa. Different estimates of overall potential arise in part from differing utilisation of the same data.

Biomass potential estimates are most often discussed in terms of a hierarchy of opportunity: *theoretical; technical; economic;* and *realistic*. Different studies interpret these terms in different ways making comparison difficult, and increasing the risk of misunderstanding. Yet while differences in definitions can create controversy and be detrimental to effective communication they do not by themselves account for why the range of estimates is so large.

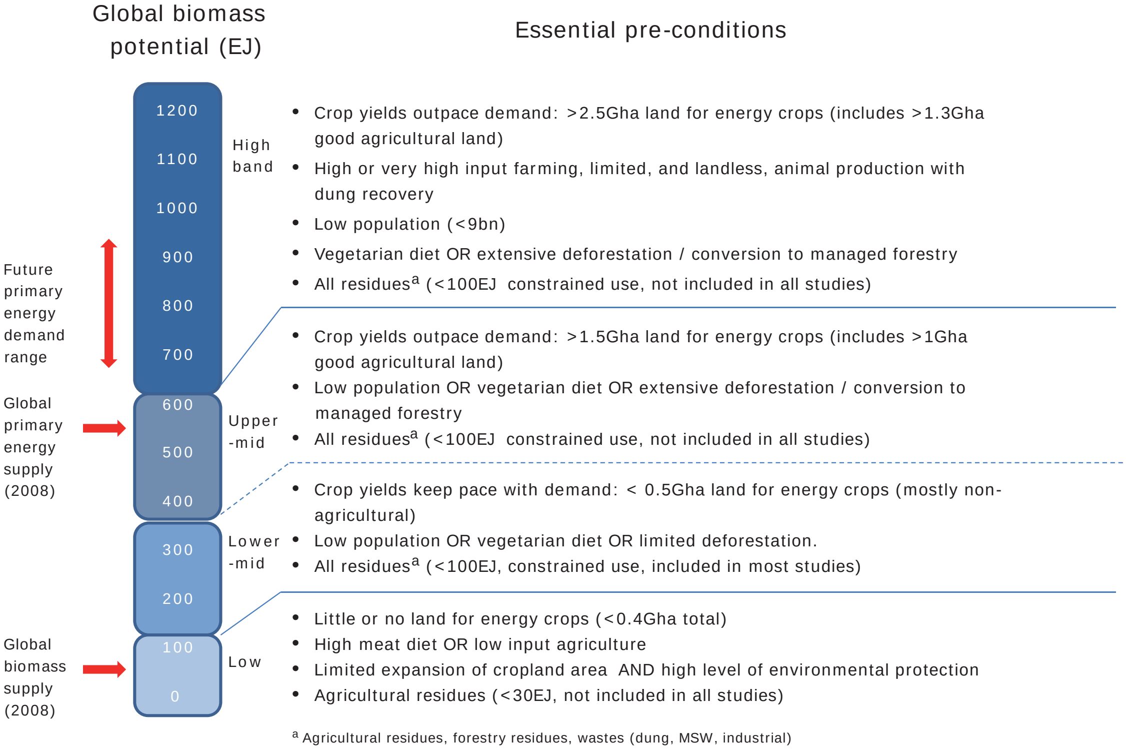
Biomass potential estimates have also faced criticism for not using standardised and consistent methodologies. Yet the analysis in this report shows that the range of estimates is driven more by the choice of alternative assumptions than methodological differences. One area where harmonisation might be valuable however, is the use of descriptive terms that are amenable to objective definition, and avoid misinterpretation. Terms such as *abandoned land* and *surplus forestry* may risk misunderstanding when used to describe large areas of the planet’s surface.

What assumptions underpin estimates of biomass potential?

Biomass potential studies can be broadly divided into two categories, 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*. Because many of the most important factors affecting biomass potentials cannot be predicted with any certainty, all these estimates must be viewed as *what if* scenarios rather than predictions. The assumptions leading to the full range of global biomass potentials found in the literature reviewed are described in Figure ES1 and elaborated below:

- Estimates up to ~100EJ (~1/5th of current global primary energy supply) assume that there is very limited land available for energy crops. This assumption is driven by scenarios in which there is a high demand for food, limited intensification of food production, little expansion of agriculture into forested areas, grasslands and marginal land, and diets evolve based on existing trends. The contribution from energy crops is

Figure ES1: Common assumptions for high, medium and low biomass potential estimates



High band:

- Crop yields outpace demand: >2.5Gha land for energy crops (includes >1.3Gha 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)

Upper-mid:

- Crop yields outpace demand: >1.5Gha land for energy crops (includes >1Gha 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)

Lower-mid:

- Crop yields keep pace with demand: < 0.5Gha 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)

Low:

- Little or no land for energy crops (<0.4Gha total)
- 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, MSW, industrial)

correspondingly low (8-71EJ). 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.

- Estimates falling within the range 100-300EJ (roughly half current global primary energy supply), all assume that food crop yields keep pace with population growth and increased meat consumption. Little or no agricultural land is made available for energy crop production, but these studies identify areas of marginal, degraded and deforested land ranging from twice to ten times the size of France (<0.5Gha). In scenarios where demand for food and materials is high, a decrease in the global forested area (up to 25%), or replacing mature forest with young growing forest is also assumed. Estimates in this band include a more generous contribution from residues and wastes (60-120EJ) but this is partly because a greater number of waste and residue categories are included.

- Estimates in excess of 300EJ and up to 600EJ (600EJ is slightly more than current global primary energy supply) all assume that increases in food-crop yields will outpace demand for food, with the result that an area of high yielding agricultural land the size of China (>1Gha) becomes available for energy crops. In addition these estimates assume that an area of grassland and marginal land larger than India (>0.5Gha) is converted to energy crops. The area of land allocated to energy crops could 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 band a high meat diet could only be accommodated with extensive deforestation. It is also implicit that to achieve the level of agricultural intensification and residue recovery required, most animal production would have to occur in feedlots. Where included, the role of residues and wastes is in the 60-120EJ range.

- Only extreme scenarios envisage biomass potential in excess of 600EJ. The primary purpose of such scenarios is to illustrate the sensitivity of biomass estimates to key variables such as population and diet, and to provide a theoretical maximum upper-bound.

Exploiting the potential in the low band of estimates could make an important contribution to future global primary energy supply through a combination of residues, wastes, and energy crops grown on different land types. Moving from the lower to the middle bands implies a dominant role for energy crops and requires increasingly ambitious assumptions about improvement in the agricultural system, and changes in diet.

Energy, food and sustainability

Societal preferences around food, energy and environmental protection will be key determinants in the extent to which biomass is used to provide energy services, and whether production happens in a sustainable or unsustainable way. Some of the changes needed to make space for large amounts of biomass for energy go against existing global trends: for instance, the trend for increasing meat consumption as incomes rise. Others are controversial: for example environmental and social acceptability of land-use change.

The biomass potential from energy crops is intrinsically linked to the demand for food and how it will be met. Although there is potential for improvement in agricultural productivity, there is uncertainty over the magnitude of these improvements, what may drive them, and the consequences they may entail. Studies whose primary objective is to quantify biomass for bio-energy tend to be more optimistic about the productivity and efficiency gains that can be achieved in the agricultural and food systems than those that seek to address future food security.

The need for better evidence

Research and experimentation has the potential to narrow some areas of uncertainty and create evidence that will sustain a more informed debate on key ethical questions. More work is needed in understanding the future productivity of both food and energy crops, and how energy and other inputs could affect it; the implications of increased intensification; the causal link between productivity increases and land availability. Water is another critical issue which could constrain future productivity of both food and energy crops, and needs to be better understood at a regional level. Integration of food and biomass production for energy could present benefits. This 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 appropriate regulation is considered pre-requisite for sustainable implementation, there is an opportunity to monitor the efficacy of regulatory approaches such as biomass sustainability certification and use this real world experience to inform decisions.

Issues and implications for policy

Seeking to predict future global food and biomass supply remains a highly speculative endeavour. There are uncertainties that cannot be resolved, and trade-offs that will always be contested, such as land-use choices and both positive and negative environmental impacts. Nevertheless, the literature indicates that there is considerable potential to expand biomass before these more contested elements begin to dominate. Doing so could assist understanding of impacts and implications. Policy-making in an area beset by data gaps, scientific uncertainties and ethical debates is necessarily difficult. Moreover, policies related to diet, agriculture and land use are at least as important as those focused on bio-energy per se.

However, the following broad areas for policy action could help address the opportunities and risks associated with biomass production for energy:

1) A short run focus on tangible opportunities could expand biomass deployment while addressing sustainability concerns. At a global level concentrating on how the first 100EJ could be made available sustainably would improve understanding of what is possible and the level of effort involved in going to higher levels of biomass use.

2) Address key uncertainties through research and experimentation, for example in relation to suitability of so-called marginal and degraded lands, integration of food and biomass for energy systems, implications of energy crops on water use at regional level, and the environmental implications of land use change and related carbon flows.

3) Develop environmental and land use regulation and sustainability standards that set biomass for energy, and agricultural systems, on a sustainable path.

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Glossary

AR	Agricultural residues
AY	Attainable yield
EC	Energy crops
F	Forestry
FY	Farm yield
FAO	Food and Agriculture Organisation of the United Nations
FR	Forest residues
GAEZ	Global Agro-Ecological Zone (model)
GIS	Geographic Information Systems
GLUE	Global Land Use and Energy (model)
GM	Genetically modified
HHV	Higher heating value
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Global Environment (model)
IPCC	Intergovernmental Panel on Climate Change
LPJmL	Lund-Potsdam- Jenna managed Land (model)
MSW	Municipal solid waste
NPP	Net primary production
OECD	Organisation for Economic Co-operation and Development
SRES	Special Report on Emission Scenarios (IPCC)
TPA	Technology and Policy Assessment
TY	Theoretical yield
UKERC	UK Energy Research Centre
USD	United States Dollar
W	Wastes
WBGU	German advisory council on climate change.
WHO	World Health Organisation
WUE	Water use efficiency

Units

adt	Air dry tonnes
bn	billion
EJ	Exajoule (10^{18} joule)
Gha	Gigahectare (10^{9} hectare)
GJ	Gigajoule (10^{9} joule)
GJ.ha^{-1}	Gigajoule per hectare
ha	Hectare (10,000 square meters)
Mha	Megahectare (10^{6} hectare)
Mha.yr^{-1}	Megahectare per year
MJ.kg^{-1}	Megajoule per kilogram
Mt	Million tonnes
odt	Oven dry tonnes
pa	Per annum
yr	Year

1. Introduction

The UK Energy Research Centre's Technology and Policy Assessment (TPA) function was set up to address key controversies in the energy field through comprehensive assessments of the current state of knowledge. It aims to provide rigorous and authoritative reports, while explaining results in a way that is useful to policymakers. This report addresses the following question:

> *What evidence is there that using biomass to supply modern energy services can make a major contribution to future global energy supply, without unacceptable consequences?*

1.1 The risks and rewards of energy from biomass

Using biomass to provide energy services is one of the most versatile options for increasing the proportion of renewable energy in the global energy system. There are many commercially available technologies that can provide heat, electricity and transport fuels from biomass feedstocks. A broad range of novel conversion and feedstocks technologies is also being researched and developed.

At the political level, interest in bio-energy is motivated by four main considerations: rising energy prices, energy security, climate change and rural development (GBEP, 2008). Many Governments (including the G8 plus five[1] and all European member states) have given bio-energy a role in their energy strategies and plans and have introduced policies to increase deployment (GBEP, 2008, Faaij, 2006). Energy scenarios, such as those developed by the International Energy Agency (IEA) and the Intergovernmental Panel on Climate Change (IPCC) also indicate that bio-energy could make a major contribution to a future low-carbon energy system (IEA, 2010) (IPCC, 2007).

Biomass, however, is a diverse and heterogeneous resource. Potential feedstocks include conventional crops and forestry products, agricultural residues, waste materials, and specially cultivated energy crops such as coppiced wood and perennial grasses. Feedstocks may also be produced domestically or imported. The availability of these materials tends to be intertwined with activity in other major economic sectors, including: farming, forestry, food processing, paper and building materials (Faaij, 2006). Impacts on these sectors from increased biomass use are almost inevitable as feedstocks may be diverted from established markets, and the way in which land resources are used may be changed.

Future technical advances will also play an important role in determining availability: productivity gains in the agriculture and forestry sectors may increase biomass supply, while new sources of demand, for instance bio-plastics and chemicals, may constrain it. A complicating factor in the design of biomass supply chains is that the composition of feedstocks – their chemical structure, moisture content, etc. – is

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[1] The G8 countries are Canada, France, Germany, Italy, Japan, Russia, the United Kingdom and the United States. The plus five are the five leading emerging economies: Brazil, China, India, Mexico and South Africa.

highly variable. Different grades of biomass may have restricted applications or may need to be blended to meet the specifications of a particular conversion process; here also, future technical developments could have an important impact. The role that bio-energy may play in the future energy system is thus fundamentally constrained, not only by the availability of biomass, but by the suitability of the biomass that is available to meet a portfolio of competing demands. It may represent an opportunity: the chance to create a new industry, reduce greenhouse gas emissions, and mitigate the impacts of conventional agriculture. Alternatively, it could exacerbate existing economic, environmental and social problems: increasing competition for resources and land.

Expanding the use of biomass to make a major[2] contribution to the global energy mix would require significant and sustained investment, both to develop sustainable sources of supply, and to deploy the technologies that can make an efficient use of a wide range of biomass feedstocks. In this context, estimates of the current, and future, biomass resource underpin many of the strategic investment and policy decisions that must be made. Investments in new technology, for example, may be justified on the basis that a large, and accessible, resource exists. Similarly, the prominence given to biomass in international negotiations as a means to mitigate climate change depends on both a quantification of the resource and the impacts associated with its development.

Moving to a future where biomass supplies a significant proportion of global energy demand would also require large scale and systemic change. Estimates of biomass potential are conceptually interesting because they provide a lens through which such system level changes can be examined. They also spur discussion around how to bring about the necessary changes in behaviour, land-use and infrastructure, and, indeed, whether such changes are desirable or politically achievable.

1.2 Objectives

The specific objectives of this report are to:

- Clarify the conceptual, definitional and methodological issues relevant to assessing global biomass potentials.
- Examine, and disaggregate existing estimates of potential in order to identify what assumptions have been made and what effect these assumptions have on potential estimates.
- Discuss the evidence and criticisms around the main assumptions affecting the global biomass potential, and in particular those relating to food production.
- Consider how resource potential estimates should be used, and what inferences can be drawn.

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[2] Biomass already contributes around 10% (~50EJ) to global primary energy supply. In this context a doubling to say 20% might be considered a major contribution.

1.3 How the assessment was conducted

The topic for this assessment was selected by the TPA Advisory Group which is comprised of senior energy experts from government, academia and the private sector. The Group's role is to ensure that the TPA function addresses policy-relevant research questions. The Group noted the persistence of controversy about this topic, the existence of widely diverging views and the mismatch between the potential importance of the issue and the level of uncertainty evident in the existing literature. It was considered that a careful review of the relevant evidence could help to clarify the reasons for the diverging views, encourage more constructive dialogue between 'opposing camps' and make the issues more accessible to a non-technical audience.

As with all TPA assessments, the objective was not to undertake new research, but instead to provide a thorough review of the current state of knowledge. The general approach is informed by systematic review techniques prominent in medicine and other fields (see Box 1.1). Following this model, the assessment

Box 1.1: The Technology and Policy Assessment (TPA) approach

The TPA approach is informed by a range of techniques referred to as evidence-based policy and practice, including the practice of systematic reviews. This aspires to provide more robust evidence for policymakers and practitioners, avoid duplication of research, encourage higher research standards and identify research gaps. Core features of this approach include exhaustive searching of the available literature and greater reliance upon high quality studies when drawing conclusions. Energy policy presents a number of challenges for the application of systematic reviews and the approach has been criticised for excessive methodological rigidity in some policy areas (Sorrell, 2007). The UK Energy Research Centre (UKERC) and Imperial College has therefore set up a process that is inspired by this approach, but is not bound to any narrowly defined method or technique.

The process undertaken for each assessment includes the following components:

- Publication of Scoping Note and Assessment Protocol.
- Establishment of a project team with a breadth of expertise.
- Convening an Expert Group with a diversity of opinions and perspectives.
- Stakeholder consultation.
- Systematic searches of clearly defined evidence base using keywords.
- Categorisation and assessment of evidence.
- Review and drafting of technical reports.
- Expert feedback on technical reports.
- Drafting of synthesis report.
- Peer review of final draft.

began with a Scoping Note[3] that summarised the debate and identified the potential contribution that a TPA assessment could make. This identifies several sources of controversy including: a wide range of estimates available in the literature, confusion over key definitions, a high level of uncertainty about how estimates should be used to inform policy decisions, and an enduring debate about whether it is right to use biomass and land to produce transport fuels instead of food.

The objectives of this assessment were designed with these issues in mind. An Expert Group was established to guide the project and the Scoping Note was circulated to key stakeholders. This led to further recommendations on the appropriate scope and focus of the assessment. In light of this debate the review focussed on global forecasts published after 1990 only. Country specific studies were excluded, as were studies that dealt only with a single aspect of bio-energy production. The agreed approach is set out in an Assessment Protocol.[4]

The systematic review identified over 90 studies with a focus on the global potential of biomass and bio-energy. Of these, 28 contained original analysis and provide the primary evidence base for this review (see Chapters 3 and 4).

1.4 Structure of report

This report is presented in 6 chapters.

Chapter 1 – sets out the high level rationale for a systematic review of global biomass potential estimates. It describes the detailed objectives of this study, and introduces the TPA methodology.

Chapter 2 – examines controversial and persistent issues that affect biomass potential assessment in more depth. This chapter also provides essential background on biomass conversion technologies, global land use and energy demand.

Chapter 3 – reviews key concepts underpinning biomass potential assessment and the methods used to calculate them.

Chapter 4 –describes the results that can be found in the literature and the assumptions that underpin them. This chapter concludes with a summary of assumptions that are pre-requisite to achieving different levels of biomass supply.

Chapter 5 – explores persistent and enduring uncertainties, focussing in particular on food and energy crops productivity assumptions, water use and pre-conditions for deployment.

Chapter 6 – presents a summary of insights and conclusions.

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[3] Available from: www.ukerc.ac.uk/support/TPA%20Overview

[4] Available from: www.ukerc.ac.uk/support/TPA%20Overview

2. Energy from biomass: sources of contention and essential context

2.1 Controversies surrounding biomass potential estimates

Addressing the question "*what is the global biomass potential?*" is a challenging task. There are many alternative methodologies that can be applied to the problem, but they all have limitations. One of these is that the concept of *potential* can be interpreted in many different ways. Stating a definition necessitates taking a stance on the price that you are prepared to pay in terms of the *economic, social* and *environmental* impacts[5]. The fewer impacts (or changes) you are prepared to accept the lower your estimate of the potential will inevitable be. Arguably there is no single or correct answer.

Yet despite its intractable nature, this question is one of the perennial subjects tackled by the bio-energy research community. It should not be too surprising, however, that these investigations lead to a range of estimates and fertile ground for debate. Sources of controversy and contention around biomass potential estimates include the following broad points.

- There is a very wide range of estimates – it is argued that this confuses policy makers, impedes effective action and fosters uncertainty and ambivalence about using biomass for energy purposes (Lynd, et al., 2011a).
- There are concerns about the inter-linkages between biomass, bio-energy, and other systems. Most notably, conflicts are foreseen with food supply, and water use, biodiversity and land use. The fear is that the benefits offered by increased biomass use will be outweighed by the costs[6] (Searchinger, et al., 2008, Eide, 2008).
- There is no single method or accepted approach for biomass potential assessments – it is argued that standardised and consistent methodologies are needed (BEE, 2008).

These points contribute to a general sense of unease about the future role of bio-energy, and whether it presents a genuine opportunity or is a utopian vision that stands little chance of being realised.

It is important to recognise that discussion of biomass-for-energy potentials (hereafter referred to as biomass potentials) does not take place in a vacuum. There has been a growing awareness that our existing agricultural system is coming under strain as the global population expands and consumption of land-intensive foods increases – and in particular dairy products and meat[7] (Godfray, et al., 2010). Problems that need to be addressed to keep pace with growing demand include: land and water scarcity, climate change and rising energy prices, in addition to a declining growth rate for cereal yields (Fischer, et al., 2009).

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[5] Depending on the definition of potential you select, this may influence your choice of methodologies and data sources, your selection of key assumptions and system constraints might also be affected.

[6] It is also argued that ineffective assessment of inter-linkages leads to confusion in the public and scientific debate, and this results in conflicting views (Lysen, et al., 2008).

[7] Currently about 1/3rd of global cereal production is fed to animals, but the conversion efficiency of plant into animal matter is only ~10%. It follows, therefore, that more people could be supported from the same amount of land if they were vegetarians (Godfray, et al., 2010, FAO, 2003).

Concern about food security has also been exacerbated by the dramatic rises in food prices that occurred in 2007/8 (Piesse, et al., 2009). Reacting to these price spikes, commentators have argued that the international policy-making community has an obligation to redress 30 years of complacency towards deficiencies in the global food system including low levels of agricultural investment (Headey, et al., 2008). There are also calls for a fundamental revaluation of agricultural production and the natural resources it depends on, especially land and water (von Braun, et al., 2008). Set against this background of concern, the production of biomass for energy purposes may easily come to be viewed as an additional pressure on a system that is already stretched (see for example Godfray et al.(2010), GOS (2011)).

Researchers who are optimistic about the prospects for bio-energy argue that significant biomass resources exist that are either underutilised, or poorly utilised – e.g. agricultural and forestry residues. Moreover, there is sufficient land available for dedicated energy crops to make a meaningful contribution to global energy supply – demonstrated by the fact that in many parts of the world land has been abandoned, taken out of agricultural production or is inefficiently used. It may also be pointed out that biomass is such a diverse resource that there are likely to be many niche markets and opportunities, even if large scale deployment of dedicated energy crops is restricted in some areas. Nor does the desire to ensure the global population is adequately fed invariably conflict with the desire to ensure it has access to energy services. In some areas there may be beneficial synergies: food crop residues may be used for energy purposes, and perennial energy crops may also be used to mitigate some of the environmental impacts of intensive agriculture – such as nitrate run-off and soil erosion (Wicke, et al., 2011b, Berndes, 2008). Using biomass to provide energy services in developing countries may even help prevent wastage in food supply-chains and provide a route for the introduction of sorely needed agricultural infrastructure and knowhow (Lynd, et al., 2011b). The introduction of measures such as feedstock certification and the broader sustainability debate around bio-energy could also have positive spill-over effects on the rest of agriculture. Bio-energy 'done right', it is argued, represents an opportunity that society cannot afford to miss (Tilman, et al., 2009, Dale, et al., 2010).

Box 2.1: Food vs. fuel

By far the most heated public debate about bio-energy has been around the production of petrol and diesel substitutes[8] from commodity agricultural crops such as maize, wheat, sugar-cane and soy. The development of these biofuels has largely been supported by subsidies and other policy incentives but they have come to be viewed increasingly negatively in a debate characterised as *food vs fuel*.

The principal argument against producing transport fuels from commodity crops is that it will increase competition for land, thereby driving up the price of food and setting in

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[8] bioethanol and biodiesel

motion a cascade of undesirable indirect effects. For example, it is argued that increased demand will not only cause the poor to suffer but will lead to increased conversion of pasture and forested land to arable production. This land use conversion may be associated with greenhouse gas emissions if, for instance, newly exposed carbon rich soils begin to oxidise, and these emissions could negate many of the environmental benefits that provided the rationale for supporting biofuels in the first place. Some of the more extreme claims include that biofuels will lead to famine, deplete water resources, destroy biodiversity and soils, as well as being primarily responsible for the food price spikes that occurred in 2008 (Eide, 2008) (Mitchell, 2008).

Those seeking to counter these arguments acknowledge the potential for competition but question both the *scale of the effect* and the *direction of travel*. In 2007/2008 roughly 110Mt of cereals (~10% of global production) was used to produce bioethanol, but because one of the co-products of ethanol production is a protein rich animal feed, the net additional demand for cereals would have been less – perhaps as little as 6% of global production (FAO, 2009) (Keller, 2010). It is also argued that the 2008 price spikes could better be attributed to a multitude of factors *in addition to biofuels*. These include: the depreciation of the US dollar, increased oil prices, export restrictions on rice, weather shocks leading to poor harvests is some regions, and increased meat consumption in China and India (Headey, et al., 2008). The direction of travel is also important because it is not envisaged that an ever larger proportion of arable land should be used to produce biofuels using existing – *1st generation* – technology. Rather, it is assumed that technological advances will lead to new – *2nd generation* – technologies able to convert residues and waste products into fuels. Moreover, it is envisaged that agricultural productivity will be increased, possibly making land available for energy crop production alongside food production, and that marginal and fallow lands will be used, thereby minimising competition with food and limiting deforestation (Rathmann, et al., 2010).

The nature and tone of this debate has itself been a cause of discussion, with some prominent scientists noting that "in the United States the policy dialogue has become increasingly polarized, and political influence seems to be trumping science" (Tilman, et al., 2009). In context of total global energy consumption, however, transport biofuels provide only a small contribution to primary energy (~3EJ, <1%) and are only one aspect of the broader bio-energy debate (IPCC, 2011).

2.1.1 Critical issues that determine the global biomass potential

Many of the studies that are discussed in this report include critiques of biomass potential assessments. These criticisms provide insight into what practitioners consider to be the most important issues. Because global potential estimates are derived from models, these criticisms concern both the structure of the models, and the parameters that underpin them. Generally speaking, however, there is

broad agreement about the most important factors affecting the contribution biomass might make to primary energy supply. These are:

- The availability of land.
- The productivity of the biomass grown on the land.
- Competition for alternate uses of the land, the biomass, and for the waste materials derived from the biomass (Berndes, et al., 2003).

Concern about the lack of consistency between estimates has also been the impetus for recent work seeking to harmonise assessment methods and better understand the reasons for discrepancies[9]. Initial results found that disparities in estimates could be attributed to four key factors:

- Ambiguous and inconsistent definitions of resource potential.
- A lack of consistent and detailed data on (current) biomass production and land productivity.
- Ambiguous and varying methods for estimating current (and future) biomass production and availability.
- Ambiguous and varying assumptions used to estimate factors external to the modelled system (such as land use and biomass production for food and fibre purposes) that might influence potentials[10] (BEE, 2008).

Other criticisms concern the parameter values used to drive the models. Essentially, these are the assumptions that underpin descriptions of future land availability, biomass productivity, and competing uses. The following parameters have been identified as particularly important:

- Global population.
- Per capita food consumption and diet.
- The potential to increase crop yields (and to close the gap between optimal yields and those achieved by farmers).
- The impacts of climate change (interactions with land, water availability, and crop yields).
- The availability of water.
- Areas required for nature conservation (biodiversity).
- Soil degradation and nutrient availability. (Thrän, et al., 2010, Berndes, et al., 2003, Lysen, et al., 2008).

These issues are discussed in more detail in Chapters 4 and 5.

2.2 Biomass potentials in context: global energy consumption and land-use

The discussion of biomass potentials inevitably involves comparing figures for the quantity of energy produced and the amount of land occupied. To put these figures in context, it is useful to have an appreciation of current land and energy use at the global level.

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[9] *Biomass Energy Europe (BEE)* (www.eu-bee.com), and *Classification of European Biomass Potential for Bioenergy Using Terrestrial and Earth Observations (CEUBIOM)* (www.ceubiom.org).

[10] Although this analysis focussed primarily on the EU region, it may be anticipated that these same factors will underlie discrepancies in estimates of the global resource potential.

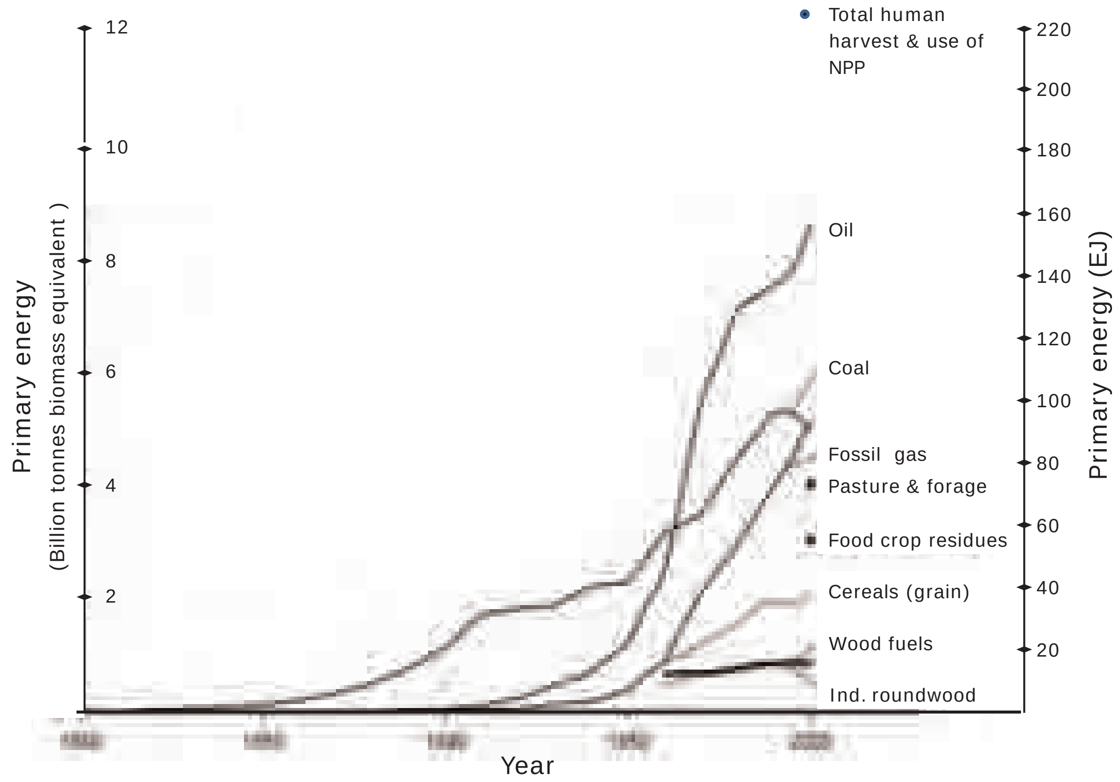
2.2.1 Global energy consumption

In 2008, global primary energy[11] supply and consumption was approximately 550EJ. The majority of this (>90%, ~502EJ) was commercially traded and was sourced from fossil fuels, nuclear and large-scale hydro electricity[12] (BP, 2011). Modern bio-energy, used to supply heat, power and transport fuels, accounted for around 2% (~11EJ). The remainder (~8%, ~40EJ) comprised traditional[13] uses of biomass including wood straw and charcoal used for cooking and heating (IEA, 2010, IPCC, 2011).

By 2050, the International Energy Agency's baseline estimate is that global primary energy demand could roughly double to ~940EJ, although if GHG emissions were constrained, the increase in demand might be limited to about ~670EJ (a 25% increase, IEA "blue map" scenario) (IEA, 2010).

Historic production levels for the main fossil energy carriers and biomass sources (food and materials) are shown in Figure 2.1. It can be seen that in the year 2000 in energy terms, the production of cereals (~40EJ), crop residues (~60EJ), pasture

Figure 2.1: Global annual production and energy content of fossil fuel, food and biomass



1 tonne biomass equivalent = 18GJ. Pasture & forage refers to the part eaten by grazing animals. Wood fuels does not include all biomass used for energy.

Source: Modified from Berndes (2008) additional data from Haberl (2007)

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[11] Primary energy refers to energy contained in a fuel prior to conversion or transformation losses.

[12] Commercially traded primary energy comprised 502EJ in 2010. This was sourced as follows: 34% oil, 30% coal, 24% gas, 6% hydroelectric, 5% nuclear, 1% renewable (BP, 2011).

[13] Globally, it is estimated that around 2.6 billion people are still reliant on traditional uses of biomass and burn wood, straw, charcoal and dung to provide basic energy services such as cooking and heating (REN21, 2010). Its use is predominantly restricted to rural areas of developing countries, and it is associated with poverty and deforestation (Ludwig, et al., 2003, Hall, et al., 1983). Traditional biomass consumption is known with far less certainty than commercially traded energy sources and may be systematically underestimated in government statistics because production and use is largely informal (IPCC, 2011, p9).

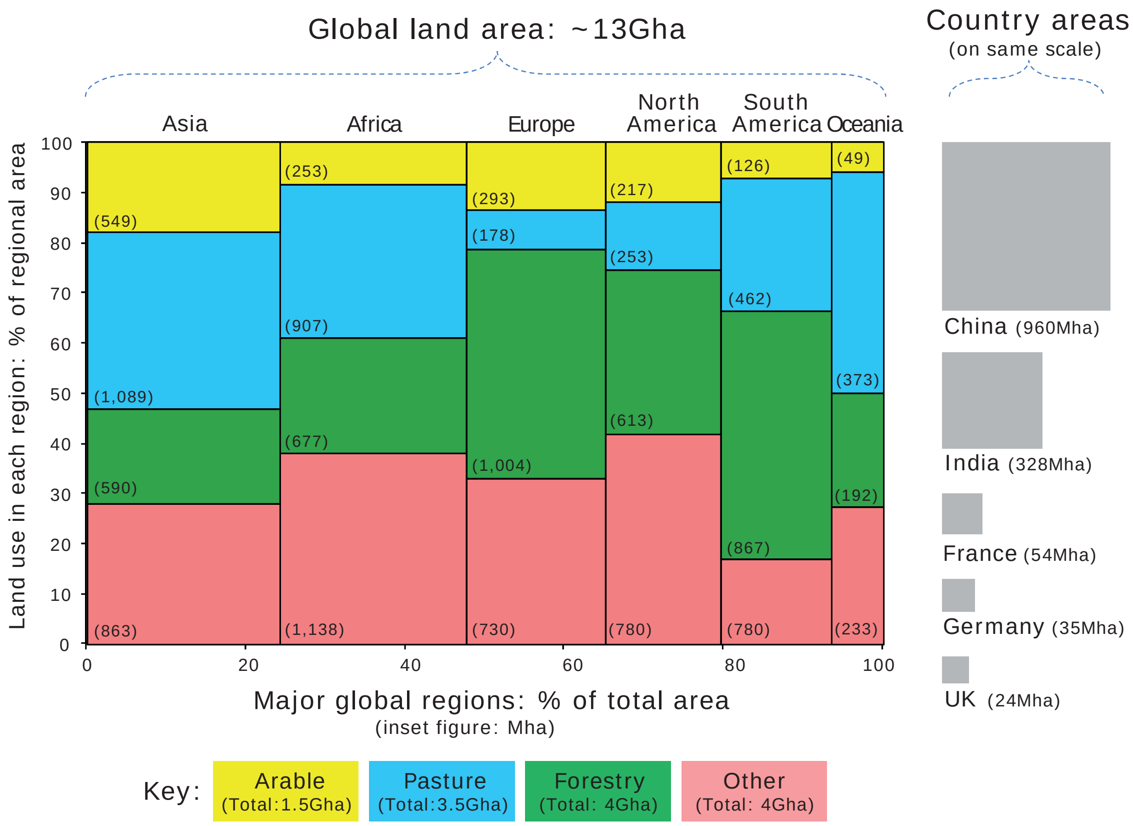
(~75EJ) and industrial roundwood (~20EJ) was substantially less than the production of fossil fuels: gas (~100EJ), coal (~100EJ) and oil (~160EJ).

The net amount of biomass produced annually by plants through photosynthesis minus the amount of energy they require for their own metabolism is known as net primary production (NPP). It is interesting to note that the total human harvest and use of NPP[14] (~225EJ), is around half the primary energy provided by fossil fossil fuels. It is also about 10-20% of total global terrestrial NPP[14] (Haberl, et al., 2007, Krausmann, et al., 2007). This comparison provides a simple illustration of the scale of the endeavour: replacing all fossil energy sources with biomass would be an undertaking of the same order of magnitude as existing global agriculture and commercial forestry together.

2.2.2 Global land use

The global land area is ~13Gha. The distribution of this land between the major global regions and the way it was being used in 2009 is shown in Figure 2.2. Overall, approximately 10% (1.5Gha) was

Figure 2.2: The global distribution of land by region and use



Source data: FAOSTAT 2009. Arable: area under temporary agricultural crops, (includes permanent crops e.g. coffee). Pasture: permanent meadows and pastures either cultivated or growing wild (wild prairie or grazing land). Forest: areas spanning more than 0.5 hectares with trees higher than 5 metres. Other: land not classified as Agricultural land and Forest area, includes built-up and related land, barren land, other wooded land, etc. For full definitions see FAOSTAT.

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[14] Haberl et.al (2007) estimate that Global Terrestrial NPP is around 1,240EJ (assuming 50% carbon content and 18.5MJ.kg^{-1}), of this they estimate that ~220 EJ (10%) is harvested and used by humans and that ~100EJ is destroyed during harvest. Krausmann et al. estimate that global terrestrial NPP is somewhat higher (~2200EJ), but estimate that a similar proportion is used by humans (~10%) and destroyed during harvest (~5%) (Krausmann, et al., 2007).

dedicated to producing arable crops, over a quarter (~3.5Gha) was used for pasture (to produce meat, milk and wool), and forestry accounted for ~30% (4Gha). The remaining ~30% (4Gha) is a broad category that includes all other uses, including barren land and built-up areas (for definitions see Figure 2.2).

Land use may change over time. Agricultural land may be expanded at the expense of forested areas; it may also be lost due to soil degradation and urbanisation. In the period 1961/63 - 1997/99, for instance, the global harvested area was increased by 221Mha (~5.5Mha.yr^{-1}), roughly equivalent to the total arable area of North America (FAO, 2003). For comparison, it is interesting to note that the current rate of loss through irreversible soil degradation (erosion) is estimated to be around 5Mha per year (Young, 1998, 1999). Urbanisation is less significant in terms of the total area, but may be important locally because many cities are located on the best agricultural land (Montgomery, 2007, Royal Society, 2009). In the period 1990-2000 net deforestation was estimated to be around 9.4Mha.yr^{-1} (the balance between deforestation occurring mainly in the tropics (14.6Mha.yr^{-1}) and afforestation occurring at temperate latitudes (FAO, 2003, p178).

Most global agricultural scenarios assume that increases in food demand will primarily be met through increases in crop yields. Nevertheless, the FAO estimate that at least ~120Mha of additional arable land will be required in developing countries by 2050 under a business as usual scenario (FAO, 2003). This is equivalent to the 2009 arable area in South America.

Box 2.2: From biomass to bio-energy: conversion technologies and options

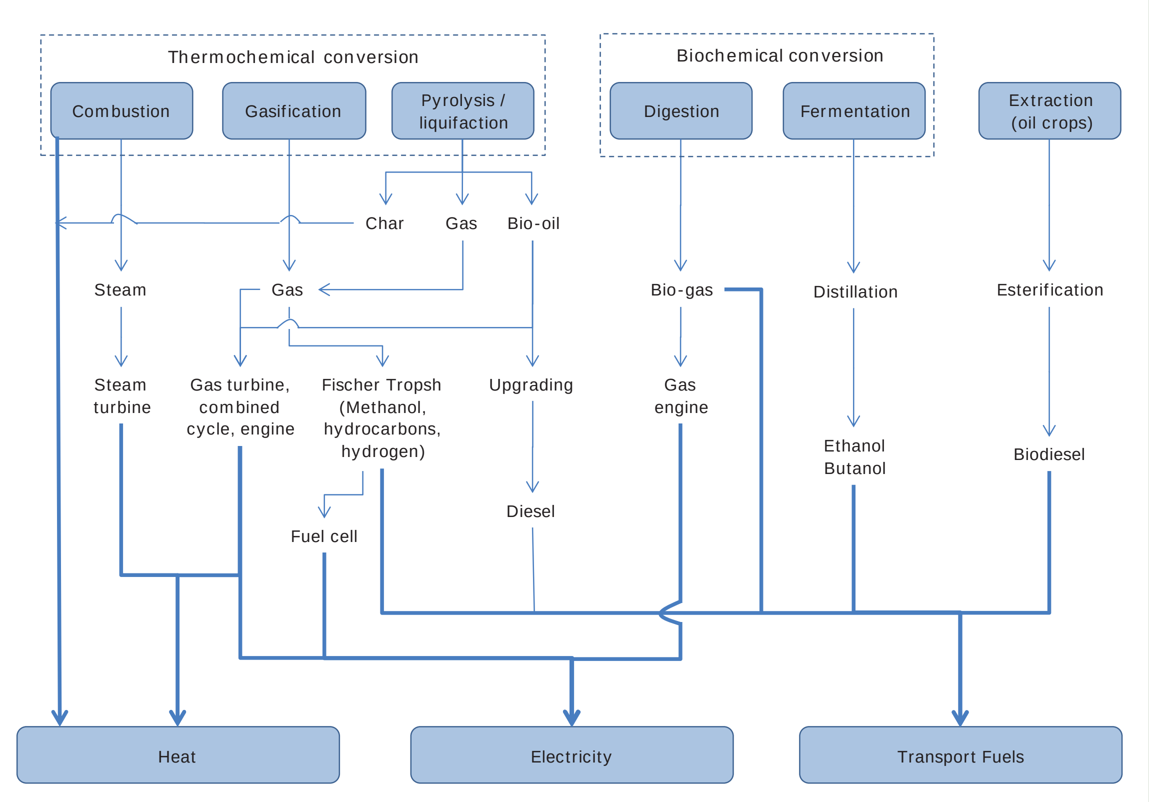
Biomass resources include an incredibly diverse range of feedstocks including dedicated energy crops, residues from agriculture and forestry, and both wet and dry waste materials (e.g. sewage sludge and municipal solid waste). Generally, drier and un-contaminated feedstocks are easier and cheaper to convert into energy carriers than wet or contaminated ones. This difference is reflected in their relative price and consequently a balance must be struck between the cost of the conversion process and the quality and price of the feedstock. It is important to note that no single conversion technology can use biomass indiscriminately in all its forms. The main biomass energy conversion pathways are shown in Figure 2.3.

Thermo-chemical pathways preferentially use dry feedstocks and include combustion, gasification and pyrolysis. Combustion involves the complete oxidation of biomass to provide heat. This may be used directly, or may be used to raise steam and produce electricity. Gasification involves the partial oxidation of the biomass at high temperatures (>500°C) and yields a mixture of carbon monoxide and hydrogen (syngas), along with some methane, carbon dioxide, water and small amounts of nitrogen and heavier hydrocarbons (Hamelinck, et al., 2004). The quality of the gas depends on the temperature of the gasification process: a higher temperature process will yield more syngas with fewer heavy hydrocarbons. Syngas may be converted into a wide range of fuels and chemicals; alternatively, it can be used to produce electricity. Pyrolysis involves heating biomass in the absence of oxygen at temperatures up to 500ºC and produces an energy-dense bio-oil along with some gas and char. This bio-oil is corrosive and acidic, but could in principle be upgraded for use as a transport fuel. Bio-oil from pyrolysis most often receives attention as a pre-treatment and densification step that could make the long distance transport of biomass more economic (Faaij, 2006).

Biochemical conversion pathways use microorganisms to convert biomass into methane or simple alcohols, usually in combination with some mechanical or chemical pre-treatment step. Anaerobic digestion is a well established technology and is suited to the conversion of homogenous wet wastes that contain a high proportion of starches and fats – e.g. food waste. Fermenting sugars and starches to alcohols using yeast is also a fully mature technology. Woody biomass can also potentially be used as a feedstock for both anaerobic digestion and fermentation processes, but requires an additional pre-treatment step in order to release the sugars that these feedstocks contain; technologies adopting this approach are being demonstrated but are not yet fully mature.

Lastly, plant oils may be extracted mechanically, reacted with alcohols or treated with hydrogen and used as substitute for diesel and other fuels.

Figure 2.3: Conversion pathways: from biomass to energy services



Source: Adapted from Turkenburg et al. (2000)

3. Estimating global biomass potentials: key concepts and methods

The systematic review undertaken for this report identified 90 studies with a focus on the global potential of biomass and bio-energy. Of these, 28 contained original analysis and provide the primary evidence base for this review. These studies are listed at the end of this chapter in Table 3.3 along with an abbreviated name that is used throughout this report. A general characterisation according to approach, timeframe, and scope is also provided in Annex 2. The estimates contained in these studies and the assumptions that underpin them are discussed in detail in Chapter 4, but prior to this discussion it is helpful to understand the terminology used to describe biomass potentials, and the alternative assessment methods used. With this objective in mind, this chapter examines how biomass potentials and biomass resources have been defined, and sets out a consistent terminology that will be used throughout this report.

3.1 What is meant by *biomass potential*?

The availability of biomass is commonly described in terms of a hierarchy of potentials. In order of decreasing size these are *theoretical, technical, economic*, and *realistic*. A *theoretical* potential estimate, for example, might be made by assuming that all net primary productivity (NPP) not needed for food could be available for bio-energy purposes. This assumption would lead to a very large and abstract number because it would ignore all competing land uses and socio-economic constraints. At the other end of the spectrum, an *economic* potential would constrain the useable quantity of biomass to the amount that could be produced at a specific price. This would lead to a smaller number, but one that was necessarily more subjective.

Adding additional constraints reduces the size of a biomass potential estimate. So, in order to compare studies on a similar basis it is important that definitions are aligned. The majority of studies considered here estimate *technical* potentials, but there is considerable disagreement between definitions. Alternative definitions in common use are described in Table 3.1.

An important distinction also needs to be made between *biomass* potentials and *bio-energy* potentials. In this report *biomass potential* refers to the gross[15] amount of energy contained in the biomass. The term *bio-energy potential* is reserved for secondary energy carriers such as electricity after conversion losses have been taken into account. The distinction is not always clear, for instance in the case where the final energy service is renewable heat the secondary energy carrier may itself be a form of solid biomass, e.g. wood pellets. The potential for ambiguity needs to be borne in mind when examining the literature to ensure that inappropriate comparisons are not made. For example, Smeets et al. (2007) define *technical bio-energy potential* as the fraction of the theoretical potential limited by the area of land and demand for food, housing, infrastructure, conservation, and taking technological advances in biomass production into account. Whereas, Hoogwijk et al.'s (2005) definition with the same name

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[15] Higher heating value

Table 3.1: The hierarchy of biomass resource potentials – alternative definitions in common use

Name	Definition
Theoretical potential / Ultimate potential	Describes the amount of biomass that could grow annually, limited by fundamental physical and biological barriers. The theoretical potential may change if conditions change, for example, due to climate change. This biomass category is not useful for analysing biomass production, except as a comparator of biomass production vs. total global primary production. (The fraction of the theoretical potential that is limited to the land surface is sometimes described as the geographic potential.)
Technical potential / Geographic potential	All you can collect from the theoretical potential (taking into account ecological constraints, land area constraints, agro-technological restraints, topographic problems etc.). An alternative definition is the proportion of the theoretical potential that is not limited by the demand for land for food, housing, etc. The technical potential may change as technology advances.
Economic potential	All biomass available up to a specified price level (taking into account the price elasticity of competitors on the market); i.e. the potential at a given price is determined by where the supply and demand curves intersect. This is highly variable as economic conditions may change dramatically over time. Moreover, markets may not exist for many biomass feedstocks, or they may be imperfect.
Implementation potential / Realistic potential	All biomass available without inducing negative social, environmental or economic impacts and respecting technology and market development issues. May be estimated using recoverability fraction or accessibility factor multipliers, reflecting what is considered the realistic maximum rates of energy use of biomass residues. Deciding what is the most appropriate multiplier to use in any particular instance is often a matter of expert judgement.

Sources: (Smeets, et al., 2007, Fischer, et al., 2001b, Lauer, 2009, Hoogwijk, et al., 2005, Offermann, et al., 2010).

excludes technological advances but includes conversion losses. It follows that these authors' results cannot be compared directly[16]. A more in depth discussion of the importance of using consistent definitions is provided in Annex 1.

A recently mooted modification to the hierarchy of potentials is the inclusion of a *sustainable potential* category. Defined as follows:

> "*The fraction of the technical biomass potential which can be developed in a way which does not oppose the general principles of sustainable development*[17]*, i.e. the fraction that can be tapped in an economically viable manner without causing social or ecological damage*" (BEE, 2008).

This idea was proposed in an attempt to improve the comparability of biomass resource assessments by harmonising assessment methods but is clearly open to interpretation as notions of *social* or *ecological damage* are partly subjective. None of the global studies identified here incorporate this particular definition in their analysis. Instead, environmental and ecological criteria are incorporated into the constraints that prescribe the transition to each successive level in the hierarchy. For the purpose of this report, however, we simply require a consistent and transparent basis for comparison. There appears, therefore, to be a case for maintaining the hierarchy as it stands but endeavouring to make the constraints and sustainability criteria explicit.

A benefit of this discussion on definitions is that we can now be more precise about the level at which studies can be compared in this review. This is the *technical biomass potential* level, defined as follows:

> *Technical biomass potential: the gross energy content of biomass that could be recovered when land required for food production, protection of biodiversity and protection of existing carbon sinks has been discounted, as well as land that is impractical to access, degraded, has low productivity, is water scarce, or requires unsustainable external inputs and nutrients* (Adapted from Hoogwijk,2005)

3.2 What sources of biomass are included in global potential estimates?

The majority of studies seek to compile an inventory of biomass resources. Potential sources of biomass, and alternative schemes for categorising them, are described in Table 3.2. At the global level the categories most often included in reports are *energy crops (EC), forestry (F), residues from forestry (FR), residues*

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[16] These authors introduce the term geographic potential to differentiate between the primary energy content of the biomass and the energy content of secondary energy carriers. This term, is also not defined consistently across all studies and to avoid confusion is not used in this report.

[17] Next to reducing global warming (greenhouse effect) and saving fossil energy, these goals include nature, soil and water conservation. These sustainability goals can both decrease (e.g. through more area dedicated to conservation and therefore withdrawn from bioenergy use) or increase the biomass potential, (e.g. if biomass from landscape conservation activities is included (BEE, 2008)).

Table 3.2: Sources and categories of biomass feedstocks

	Classification		Biomass source
Energy crops[a]	Conventional crops		Annual crops: cereals, Oil seed rape, sugar beet
	Perennial energy crops		Short rotation coppice (willow or poplar); plantation tree crops e.g. eucalyptus ; energy grasses: miscanthus, switch grass
Primary residues[b,c]	Forestry[f] and forestry residues		Short rotation forestry[h]
			Wood chips from branches, tips and poor quality stemwood
	Agricultural crop residues		Straw from cereals, oil seed rape, and other crops
	Secondary residues[b,d]	Sawmill co-product	Wood chips, sawdust and bark from sawmill operations
		Arboricultural arisings	Stemwood, wood chips, branches and foliage from municipal tree surgery operations
Wastes	Tertiary residues[b,e]	Waste wood[g]	Clean and contaminated waste wood
		Organic waste	Paper/card, food/kitchen, garden/plant and textiles wastes
		Sewage sludge	From Waste Water Treatment Works
		Animal manures	Manures and slurries from cattle, pigs, sheep and poultry
		Landfill gas	Captured gases from decomposing biodegradable waste in landfill sites

[a] Availability depends on the amount of land dedicated to the crop, and the crop yield

[b] Availability depends on activity in other economic sectors.

[c] Harvest residues: typically available 'in the field' and need to be collected to be available for further use.

[d] Processing residues: produced during production of food or biomass materials; typically available in the food and beverage industry.

[e] Post consumption residues: materials that become available after a biomass derived commodity has been used.

[f] Timber from mature forests is generally considered to be too valuable to use for energy purposes

[g] This category may, or may not, be taken to include a fraction of municipal solid waste (MSW)

[h] short rotation forestry may also be considered an energy crop in some schemes.

Source: adapted from (Faaij, 2006, Hoogwijk, 2003, E4tech, 2009) *from agriculture (AR)*, and *wastes (W)*[18]. Caution is needed, however, as not all reports include all types of biomass and there is no coherent or universally applied classification scheme. Definitions may also vary; for instance, it is estimated that around 90 different definitions of 'forest' are used in different parts of the world (Lepers et al. (2005) in Schubert et al. (2009)).

3.3 How are global biomass potentials calculated? An overview of modelling approaches

The global biomass potential and its use to provide energy services cannot be measured, it can only be modelled. Models vary in complexity and sophistication, but all aim to integrate information and assumptions from a variety of sources – databases, field trials, other models, scenarios – to elucidate some aspect of bio-energy's future development (see Box 3.1). Importantly, the structure of the model plays an important role in determining the result, and can help explain why estimates differ.

The clearest distinction is between estimates of potential that are *resource focussed*, and those that are *demand driven* (Berndes, et al., 2003). A distinction may also be drawn between studies based on their *complexity* and level of *integration* (Smeets, et al., 2007).

The least complex approaches involve the use of expert judgment to estimate the future share of cropland, grassland, forests, and residue streams available for bio-energy. The most complex involves the use of integrated models which allow multiple variables, trade-offs and scenarios to be analysed[19]. The major models, databases and scenarios are identified in Annex 2.

Resource focussed studies seek to compile an inventory of available biomass, based upon assumptions about the availability of supply side resources (principally land for energy crops and forestry, residues, and wastes). Hall et.al (1993), for example, adopts simple rules to estimate the proportion of land that might be available and suitable for energy crops; this is combined with a similarly simple estimate for residue availability[20] to give an estimate of the global potential. More recent studies have used spatially explicit models that consider the availability and productivity of land on a grid basis with a resolution down to 10km^2 (see for instance Schubert et al. (2009)).

A typical approach to conducting a resource focussed study is shown in Figure 3.1. Crucially, the results of the assessment are highly dependent on the methods used to quantify changes in production systems, and the boundary conditions identified at the outset (including the number of sources of biomass included). Expert judgement also plays in important role in many assessments.

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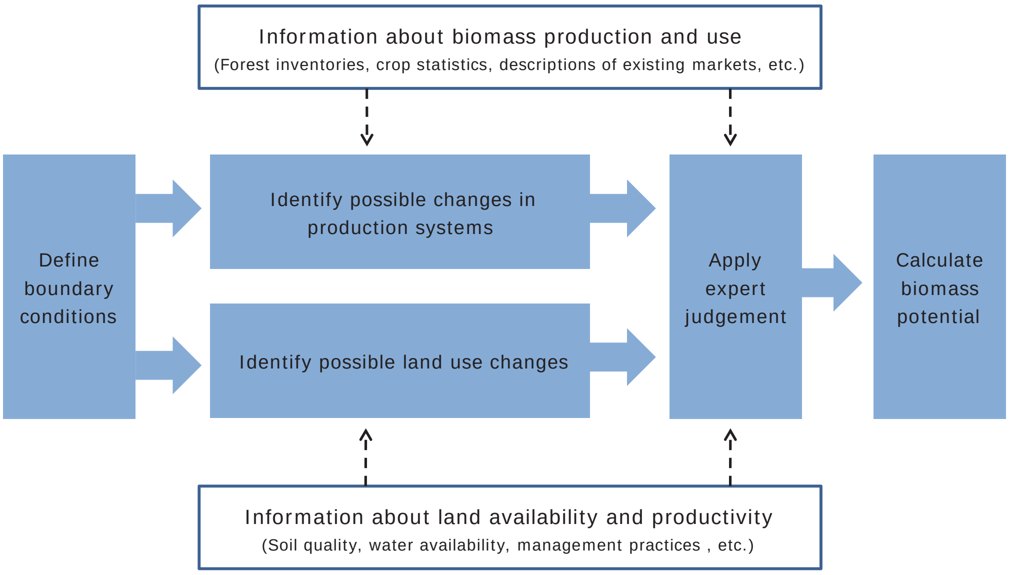
[18] Categories used in global level assessments tend to be more highly aggregated than those used for country level assessments. This reflects the availability and quality of data available (Slade, et al., 2011).

[19] Smeets et al.(2007) identify three integrated models that have been used to estimate the future potential of bioenergy: the Global Land Use and Energy Model (GLUE) (Yamamoto, et al., 1999), the Integrated Model to Assess the Global Environment (IMAGE) (Leemans, et al., 1996) and the Basic-Linked System (BLS) model of the world food system (Fischer, et al., 2001b). The major models, databases and scenarios used in each report are identified in Table 3.4

[20] Residues are estimated from global agricultural and forestry production data by applying availability fractions.

Figure 3.1: A typical workflow for a resourced focussed biomass potential assessment



Source: Modified from Lauer (2009)

Demand-driven studies, in contrast, focus on the competitiveness of bio-energy compared to conventional energy sources or estimate the amount of biomass required to meet specific, exogenously imposed, targets (Berndes, et al., 2003). Many of the demand driven estimates are generated as part of wider energy-economy modelling exercises. A study conducted by the IEA in 2008, for example, looks at the issue from a top-down perspective, estimating how much demand for bio-energy there is likely to be, given future energy market assumptions, price-points, and trends for a range of different energy sources (IEA, 2008). These studies are often based on simplified cost curves and high level resource assumptions, which are themselves based on the resource-focused studies.

One of the limitations of demand-driven studies study is that the assumptions are often highly aggregate and opaque. In the IEA08 study, for instance, the uptake of biomass to serve energy markets depends on its presumed future cost, but the cost curves used are not explicit. So, although these studies provide some insight into the likelihood of biomass demand increasing in the future, they provide little insight into the size of the technical biomass potential, and the assumptions implicit in its derivation. For this reason demand-driven studies are excluded from in-depth analysis in this review.

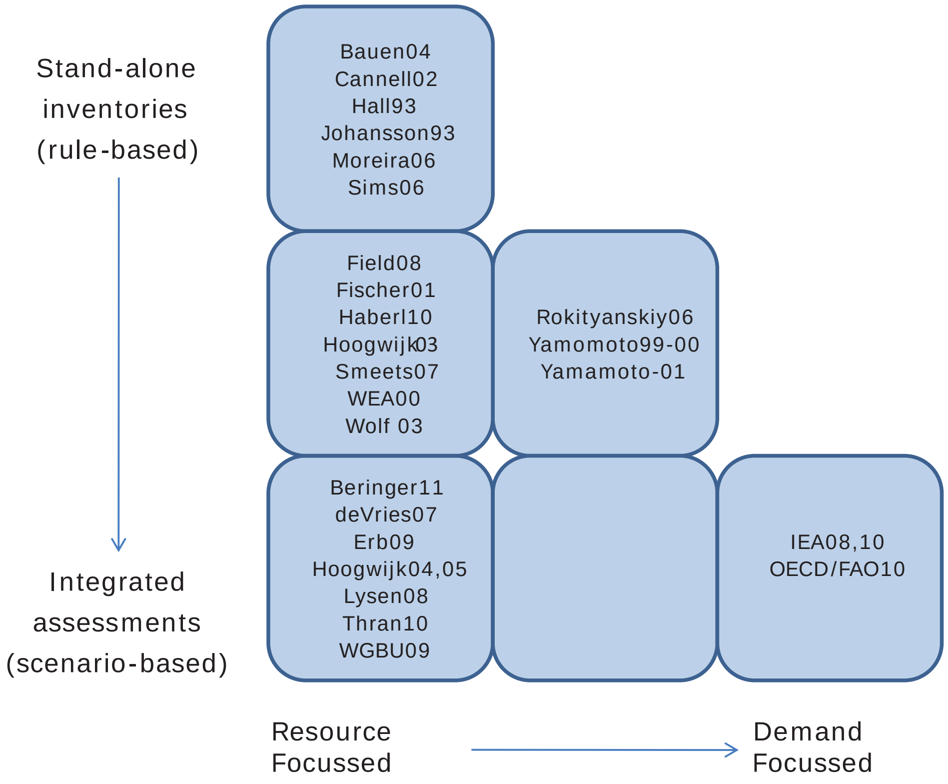
The concept of an *integrated* study is also used in many reviews and describes the ambition to combine resource and demand assessment into a unified modelling framework. The advantage of such an approach is that it can provide insights into how an expanding bio-energy sector interacts with other energy and non-energy sectors. The downside is that it may result in an unwieldy model with little transparency of assumptions, and thus difficult to interrogate (BEE, 2008). The dilemma for researchers in this area, therefore, is how to build a model that represents the real world sufficiently well to allow useful insights to be obtained, without making it so complex that it is unusable.

In practice, there is a spectrum of approaches to integration. The studies by Hoogwijk et al. (2005, 2004) for instance, examine scenarios constructed using an integrated model called IMAGE. This model combines scenarios for population growth, the level of technological attainment, farming methods and calorie consumption to estimate the area of land that might be used for energy crops. These estimates are then used to calculate biomass resources for energy use; biomass demand is not estimated or integrated.

Demand and supply are integrated to a greater extent in a series of studies by Yamamoto et al. using an integrated model called GLUE (Global Land Use and Energy model (1999, 2000, 2001). This model examines how resources may be optimally allocated to meet projected demand in different economic sectors but permits only a simplistic treatment of supply options and competing land uses.

A simple framework for categorising studies in terms of their approach is presented in Figure 3.2. – this figure also shows the abbreviated name used to identify each of the key studies. The horizontal axis describes the spectrum from resource-focused to demand-focused. The vertical axis describes the extent to which the models are integrated, from stand-alone inventories to fully-integrated (in that they consider competing uses of land driven by

Figure 3.2: A scheme for categorising global biomass potential studies according to their approach



scenarios for population and GDP growth). Mapping the studies identified in this review onto this framework illustrates that the majority can be considered resource focused.

It is also interesting to note the evolution of studies in the last 20 years. Earlier studies of biomass potential, tended to be stand-alone, "rule-based", assessments, for example Hall et al. (1993). As the science and methodology has progressed, however, estimates have adopted spatially explicit assessment methodologies and scenarios as the basis for analysis (see for example Hookwijk et al. (2005). There has also been a clear move towards the use of scenarios to explore a range of possible futures and the sensitivity of estimates to changes in demographics, behaviour and economic growth projections. It is also worth noting that none of the studies claims to be definitive and there is a general acceptance that there is no single right answer.

Box 3.1: Models, scenarios and databases

Models combine information from a range of sources including sub-models, scenarios and databases. Models and modelling approaches used in more than one study include the integrating models: IMAGE, GLUE, and BLS; and crop yield models: LPJmL and FAO GAEZ. These are broadly applicable models and are also used to examine food crop potentials.

Integrating models:

- IMAGE2: Integrated Model to Assess the Global Environment – describes land-use changes considering projected future driving forces like food demand, crop yields and climate change (MNP, 2006).
- GLUE: Global Land Use and Energy Model – a systems dynamics economics model, describes how regional population and GDP forecasts drive competition for land between different sectors (Yamamoto, et al., 1999).
- BLS: Basic-Linked System (BLS) model – an applied general equilibrium model. It views national agricultural systems as embedded in national economies and models national commodity production and consumption, financial and trade flows at the national and global level (IIASA).

Yield models:

- GAEZ: Global Agro-Ecological Zones methodology – provides a standardised method to characterise regional climate, soil and terrain conditions relevant to agricultural production. A crop modelling and environmental matching process is used to identify where, and how well, different crops will grow and estimate the maximum potential and agronomically attainable crop yields (Fischer, et al., 2000).
- LPJmL: Lund–Potsdam–Jena managed Land – simulates biophysical and biogeochemical processes to model the large-scale distribution of the most important

crops worldwide, using the concept of crop functional types. The model estimates productivity[21] and yield values and permits different management options (irrigation, treatment of residues, intercropping) to be investigated (Bondeau, et al., 2007).

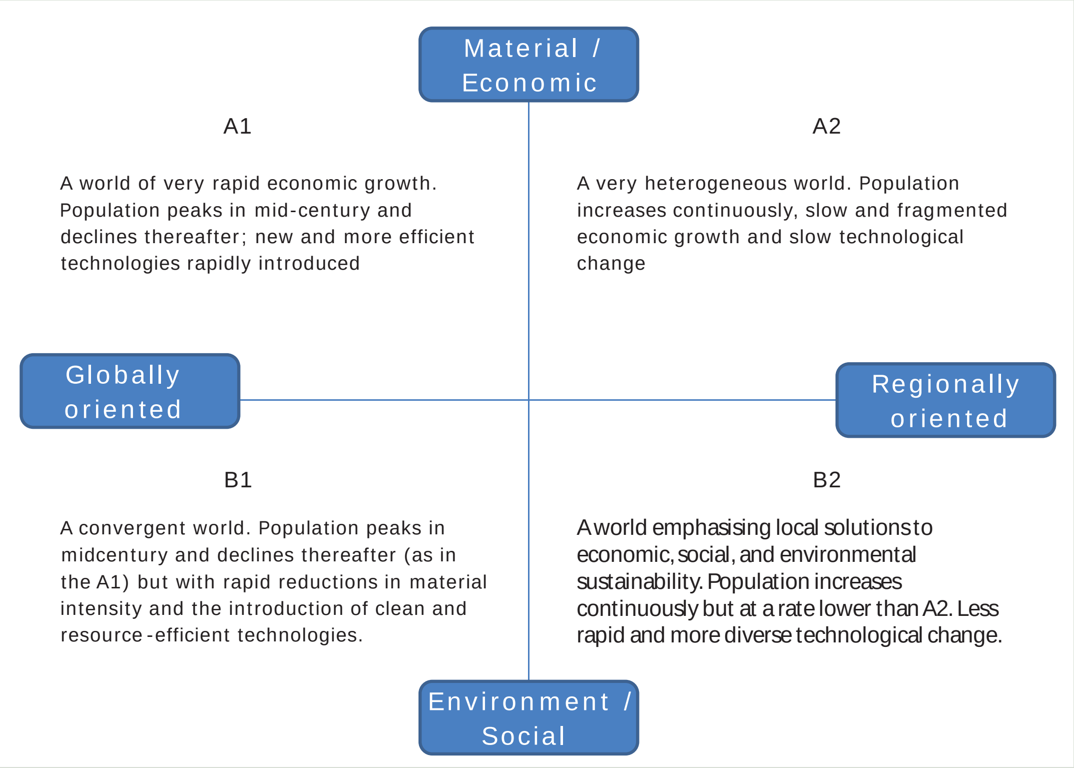
Scenarios:

- Scenarios aim to provide alternative narratives for how key parameters, such as global population, might evolve in the future. The most prominent scenarios used in bio-energy potential assessments are those described in the IPCC special report on emission scenarios (IPCC, 2000) and known as the IPCC-SRES scenarios illustrated in Figure 3.3.

Databases:

- The primary data source for all assessments is FAOSTAT. This is a database of global agricultural production and land use (including forestry) collated and made publically available by the FAO. It is a heterogeneous dataset compiled from country surveys, satellite imaging data, projections and estimates. The data quality of the FAO's compilations is sometimes contested, e.g. due to politically motivated under- or over-reporting (Krausmann, et al., 2007). There are also discrepancies in time scales and spatial resolution; further problems arise from the data mixing of different remote sensing data sets (Schubert, et al., 2009). Despite these limitations, however, it remains the only comprehensive and standardized global dataset available.

Figure 3.3: IPCC SRES scenarios



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[21] Productivity and yield are related concepts. Productivity describes the quantity of product per unit time or other input (e.g. water or fertilizer). Yield describes the quantity of product per unit area or plant.

3.4 Estimating the potential of energy crops

Energy crops require land. How much land is available depends upon competing uses. How much energy can be produced depends on the fertility of the land and the yield of the crops grown upon it. The role of energy crops dominates the discussion of biomass potentials but thus far most practical experience is limited to projects implemented for reasons other than energy – e.g. commercial forestry.

3.4.1 How much land is available for energy crops?

The greatest competing use for land comes from the demand for food, animal feed and pasture. If technological improvements increased crop yields, or population decreased, or diets changed and the consumption of meat was reduced, then at least in theory, surplus agricultural land would become available. There is a historical precedent for this when during the early 1990’s around 6-7Mha (~10%) of arable land in the EU was removed from production to limit agricultural surpluses under the set-aside scheme (Boatman, et al., 1999). In the UK at least, the introduction of set-aside dominated subsequent discussions about the potential area available, and one of the motivations suggested for the introduction of energy crops was to find a potentially worthwhile use of land that was, by definition, surplus to food production requirements (Slade, et al., 2011).

In addition to the existing agricultural area, other types of land might be converted to either agricultural or energy crop use in the future. These areas include areas of marginal and degraded land, deforested and forested areas, and extensive grasslands such as the African savannah and Brazilian cerrado. But predicting the future availability of these lands is inherently problematic because they may include areas that are high in biodiversity, remote from any infrastructure, used for seasonal grazing or otherwise unavailable for myriad different reasons. Moreover, they may suffer from poor soils, have limited water availability, be unsuitable for mechanised agriculture or be otherwise poorly yielding or uncultivable.

Two broad approaches to modelling the future land availability can be distinguished: *availability factors* and *land balance models*.

The *availability factor* approach simply identifies different categories of land and multiplies the area in each category by the fraction deemed suitable for energy crops. This fraction may be informed by information about agricultural surpluses, or may be purely hypothetical. Johansson et al. (1993), for example, assume that 100% of the land removed from agricultural production in the USA (circa1993) might be available for energy crops in this region; and for Africa assume that all areas of logged forest may be suitable for reaforestation[22]. This approach has the advantage of a high level of transparency, but is simplistic and cannot capture the dynamics of competing demands for land or spatial variation in yields.

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[22] Estimates for degraded lands were taken from Grainger (1988).

Land balance models in contrast identify land areas on which crops may be cultivated (depending on soil, climate, and terrain[23]); they then exclude areas required for food production and other land uses such as urbanisation and nature conservation. The area that remains is allocated to energy crops (see for example Hoogwijk et al. (2005), Erb et al. (2009)). The advantage of this approach is that the more sophisticated models can investigate the interactions between changing food demand, climate change and land availability over time. Yet this approach has also been criticised for overestimating the land available because:

- Land suited to cultivation may be overestimated – due to failure to exclude uncultivable areas that only show up at high resolution (e.g. hills, rock, outcrops, minor water bodies, etc.).
- Land already cultivated may be underestimated – because national statistics are often incomplete and unreliable.
- Other land uses may not be recognised and excluded from the total – for example, land required for nature conservation, human settlements, and forest (Young, 1999).

A variant of the land balance approach is the use of mapping software (such as Geographic Information Systems (GIS)) to generate maps of productive areas overlaid with exclusions. For example, Wicke et al. (2011a) combine data from the Global Land Cover Database for 2000 with the World Database on Protected Areas and the Harmonized World Soil Database to analyse the global potential for biomass on salt-affected soils. Generally, however, map based approaches tend to be used at the county or regional level where high resolution spatially resolved datasets are more available.

3.4.2 The importance of food and energy crop yields

If food crop yields can be increased then agricultural land may become available for energy crops. Similarly, if energy crop yields can be increased then more energy can be produced for any given amount of land.

Crop yields are a function of the amount of sunlight, the proportion of that light intercepted by the crop, the efficiency with which it is converted to biomass by photosynthesis, and the proportion of that biomass partitioned to the harvested product (Monteith, 1977, Hay, et al., 1989). At any given location, the yield achieved will be determined by complex interactions between plant physiology, local ecology and climate, and management practices. Yields that can be achieved on poor quality soil, or in areas where water is scarce, may be far less than those achieved under optimum conditions. For the purposes of estimating the future contribution from energy crops, there are two approaches to estimating the productive yield:

- Extrapolation from case-studies and sample plots.
- Model based yields – where empirical crop models are developed to predict

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[23] Most assessments use the FAO AEZ method to match crop and land types.

the growth of specific energy crops on different soils, and using different agronomic practices etc. Alternatively, models may be used to estimate the net primary productivity (NPP) of the natural ecosystem and a proportion of this may be allocated to a hypothetical energy crop.

It is important to recognise that uncertainty about how model parameters will change with location and over time, and limitations in the number of sample plots available mean that all these methods are ultimately speculative (Berndes, et al., 2003).

3.5 Estimating the potential of agricultural residues

In contrast to the uncertainties that beset energy crop estimates, comparatively good data about the production of major food crops is collated and published by the FAO. From this data it is possible to estimate the quantity of residues produced by applying availability factors. The basic calculation for each crop is as follows:

> *Resource = Total crop * Harvest index * Recoverability – Residues dedicated to other uses*

The harvest index is the fraction of the above ground biomass that is the primary crop. In the case of wheat and barley in the UK this is ~51%, and for rapeseed it is about 30% (Kilpatrick, 2008). Because past improvements in the major food crop species such as wheat have largely resulted from increases in the harvest index rather than increases in the total biomass produced by each plant (Hay, 1995), residue production may decrease as cereal yields increase. This effect may, however, be offset by increases in total crop production.

It should also be noted that not all biomass residues will be recoverable: some may be left in the field to maintain soil fertility or may already be dedicated to existing uses – e.g. animal bedding.

3.6 Estimating the potential of wastes and residues

Robust data on waste production is not available. Consequently, attempts to quantify the resource are limited to top-down estimates of the amount of waste likely to be produced per unit of economic activity in different industrial sectors, per head of population, or per head of livestock. The basic calculation for each waste sub-category is:

> *Resource = Level of economic activity * Waste generation fraction* Recoverability*

This type of approach is generic to all the reviewed reports[24]. Estimates may also be projected into the future, moderated by judgements about the effect of economic

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[24] For example, Johansson et al. (1993), assume that Municipal Solid Waste (MSW) in OECD countries will be generated at a constant rate of 300kg per capita per year, and that 75% of this will be recoverable for energy purposes. In another example, Yamamoto et al. (1999) estimates that 20% of food supply will end up as kitchen refuse and that 75% of this could be used for energy purposes. These authors also estimate that 20% of food supply will end up as human faeces and that 25% of this could be recovered.

growth or other anticipated changes such as increased recycling rates. The principal source of variation between reports is the inclusion/exclusion of waste sub-categories in the resource inventory. The main source of data is the FAO.

3.7 Estimating the potential of forestry

Forestry residues may be estimated in the same way as other wastes: i.e. as a fraction of the unused biomass produced by existing forest industries – again relying on FAO data.

Harvesting biomass from mature forests, however, is a more controversial area. Many recent studies exclude mature forestry directly from biomass-for-energy estimates considering it better to retain the carbon stored in mature forest. The rationale for this is twofold: firstly, the impact on biodiversity would be unacceptable; and secondly, that the carbon emitted as a result of changing the land use could be significant. In its 2009 report the WBGU states that it is "doubtful whether the conservation of tropical primary forests can be combined with use of these forests for bio-energy or for material feedstocks since the ecosystem is highly sensitive to disturbance and even small-scale incursions, such as for the construction of a road, result in deforestation within a few years" (Schubert, et al., 2009). Nevertheless a number of studies include estimates of wood production from natural forests including Smeets07, Fischer01, and Yamamoto99,00,01. There is very limited data of the harvest intensity of mature forests and so the approach taken by these studies is to estimate the gross annual forest growth increment (a measure of NPP) as a proxy for the technical potential, and limit this by the fractions deemed available and accessible. Implicit in this approach is that a proportion of mature forest would become managed "re-growth" forest. This category of biomass would also overlap with traditional firewood gathering.

Table 3.3: Studies included in this review

Abbreviated name (lead author / institute and year of publication)	**Main reference**
Bauen04	Bauen, A., Woods, J. and Hailes, R. (2004) *Bioelectricity Vision: achieving 15% of electricity from biomass in OECD countries by 2020*. E4tech (UK) Ltd.
Beringer11	Beringer, T., Lucht, W. and Schaphoff, S. (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, 3, 299-312.
Cannell02	Cannell, M. G. R. (2003) Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. *Biomass and Bioenergy*, 24 97-116.
deVries07	de Vries, B. J. M., van Vuuren, D. P. and Hoogwijk, M. M. (2007) Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach. *Energy Policy*, 35 2590-2610.
Erb09	Erb, K.-H., Haberl, H., Krausmann, F., Lauk, C., Plutzar, C., Steinberger, J. K., Müller, C., Bondeau, A., Waha, K. and Pollack, G. (2009) *Eating the planet: Feeding and fuelling the world sustainably, fairly and humanely - a scoping study (Commissioned by Compassion in World Farming and Friends of the Earth UK)*. Institute of Social Ecology and PIK Potsdam, Vienna, Potsdam.
Field08	Field, C. B., Campbell, J. E. and Lobell, D. B. (2008) Biomass energy: the scale of the potential resource. *Trends in Ecology and Evolution*, 23.
Fischer01	Fischer, G. and Schrattenholzer, L. (2001) Global bioenergy potentials through 2050. *Biomass and Bioenergy*, 20, 151-159.
Haberl10	Haberl, H., Beringer, T., Bhattacharya, S. C., Erb, K.H. and Hoogwijk, M. (2010) The global technical potential of bio-energy in 2050 considering sustainability constraints *Current Opinion in Environmental Sustainability*, 2.
Hall93	Hall, D. O., Rosillo-Calle, F., Williams, R. H. and Woods, J. (1993) Biomass for Energy: Supply Prospects. IN T.B. JOHANSSON ET AL (Ed.) *Renewable Energy: Sources for Fuels and Electricity*. Washington, D.C, Island Press.
Hoogwijk03	Hoogwijk, M., Faaij, A., van den Broeka, R., Berndes, G., Gielen, D. and Turkenburg, W. (2003) Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, 25, 119 - 133.
Hoogwijk04	Hoogwijk, M. M. (2004) *On the global and regional potential of renewable energy sources*. RIVM, University of Utrecht.
Hoogwijk05	Hoogwijk, M., Faaij, A. and Eickhout, B. (2005) Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, 29 225-257.
IEA08	IEA (2008) *World energy outlook*. International Energy Agency (IEA).
IEA 2010	IEA (2010) *Energy technology perspectives 2010: scenarios and strategies to 2050*. International Energy Agency (IEA), Paris.

Johansson93	Johansson, T. B., Kelly, H., Reddy, A. K. N. and Williams, R. H. (1993) A renewables-intensive global energy scenario (RIDGES) (appendix to Chapter-1). IN T.B. JOHANSSON ET AL (Ed.) *Renewable Energy: Sources for Fuels and Electricity*. Washington, D.C, Island Press.
Lysen08	Lysen, E., van Egmond, S., Dornburg, V., Faaij, A., Verweij, P., Langeveld, H., van de Ven, G., Wester, F., van Keulen, H., van Diepen, K., Meeusen, M., Banse, M., Ros, J., van Vuuren, D., van den Born, G. J., van Oorschot, M., Smout, F., van Vliet, J., Aiking, H., Londo, M. and Mozaffarian, H. (2008) *Biomass assessment: assessment of global biomass potentials and their links to food, water, biodiversity, energy demand and economy*. Netherlands Environmental Assessment Agency MNP.
Moreira06	Moreira, J. R. (2006) Global biomass energy potential. *Mitigation and Adaptation Strategies for Global Change*, 11, 313-342.
OECD10 / FAO	FAO (2010) *OECD-FAO Agricultural outlook 2010-2019*. FAO, Rome.
Rokityanskiy06	Rokityanskiy, D., Benítez, P. C., Kraxner, F., McCallum, I., Obersteiner, M., Rametsteiner, E. and Yamagata, Y. (2007) Geographically explicit global modelling of land-use change, carbon sequestration, and biomass supply. *Technological Forecasting & Social Change*, 74, 1057-1082.
Sims06	Sims, R., Hastings, A. and Schlamadinger, B. (2006) Energy crops: current status and future prospects. *Global Change Biology*, 12, 2054-2076.
Smeets07	Smeets, E., Faaij, A., Lewandowski, I. and Turkenburg, W. (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*, 33 56-106.
Thrän10	Thrän, D., Seidenberger, T., Zeddies, J. and Offermann, R. (2010) Global biomass potentials - resources, drivers and scenario results. *Energy for sustainable development* 14 200–205.
WEA00	WEA (2000) *World energy assessment (WEA): Energy and the challenge of sustainability (Chapter 5: energy resources)*. UNDP, New York.
WGBU09	Wolf, J., Bindraban, P. S., Luijten, J. C. and Vleeshouwers, L. M. (2003) Exploratory study on the land area required for global food supply and the potential global production of bioenergy. *Agricultural Systems*, 76, 841-861.
Wolf03	Schubert, R., Schellnhuber, H. J., Buchmann, N., Epiney, A., Grießhammer, R., Kulessa, M., Messner, D., Rahmstorf, S. and Schmid, J. (2009) *Future bioenergy and sustainable land use (a report for the German Advisory Council on Global Change (WBGU)*. London and Sterling, VA, Earthscan.
Yamamoto99	Yamamoto, H., Fujino, J. and Yamaji, K. (2001) Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model. *Biomass and Bioenergy*, 21, 185-203.
Yamamoto00	Yamamoto, H., Yamaji, K. and Fujino, J. (1999) Evaluation of bioenergy resources with a global land use and energy model formulated with SD technique. *Applied Energy*, 63, 101-13.
Yamamoto01	Yamamoto, H., Yamaji, K. and Fujino, J. (2000) Scenario analysis of bioenergy resources and CO2 emissions with a global land use and energy model. *Applied Energy*, 66, 325-337.

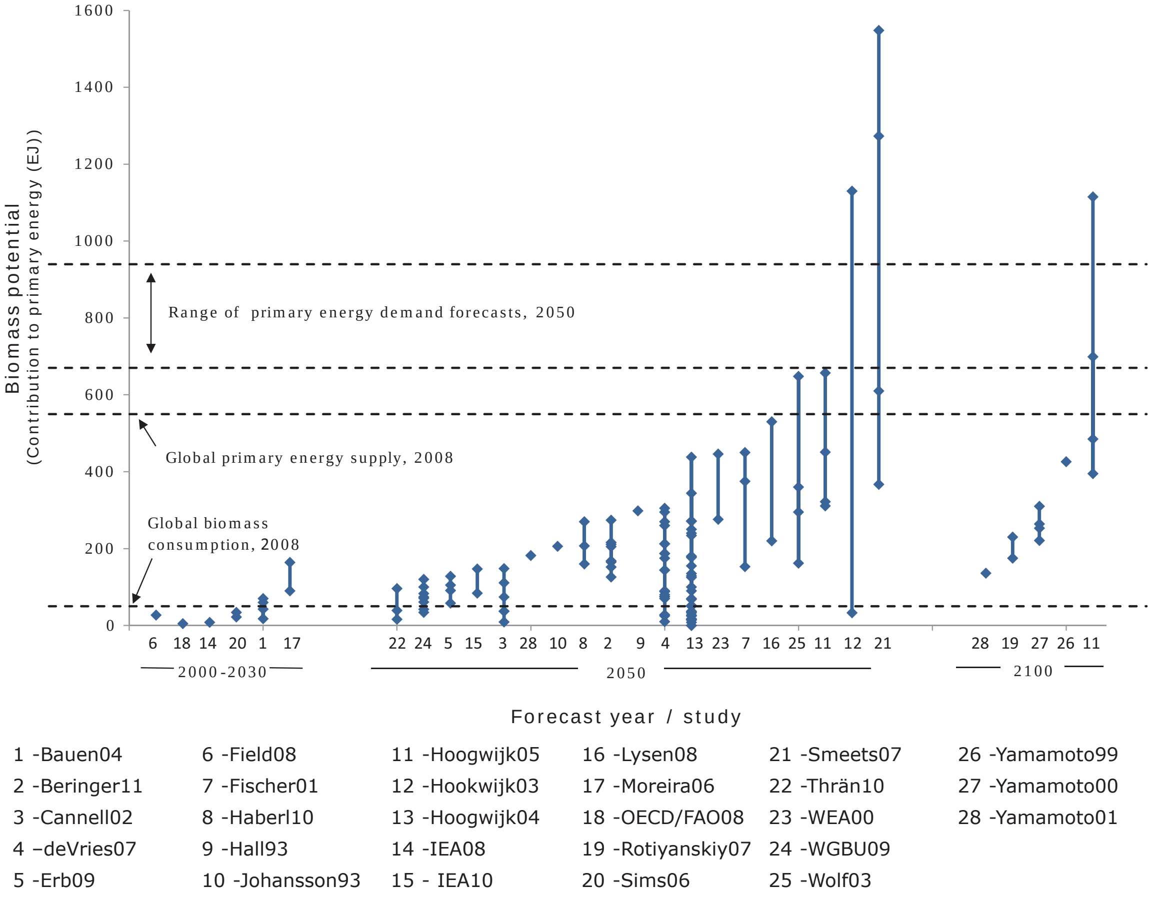
4. Quantifying the global biomass resource: results and assumptions

The studies identified in the systematic review describe over 120 estimates for the future potential of energy from biomass. Estimates correspond to three main timeframes: short term (forecasts up to 2030), mid-term (2050) and long term (2100). The majority of the data, however, is 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 (see, for example, the IPCC SRES models).

The range of potential forecasts is shown in Figure 4.1 (each vertical line represents one of the key studies). As previously noted, the range of estimates is very large. For 2050 alone, a forecast of zero is made in more than one study under certain scenarios (Hoogwijk, et al., 2003, Wolf, et al., 2003), while 1548EJ.yr^{-1} is forecast in another (Smeets, et al., 2007) – a figure roughly three times global primary energy supply in 2010 (BP, 2011). It would not be helpful, however, to merely identify an average value. This is because each individual study is attempting something different: some of the data corresponds to scenarios purposefully chosen in order to demonstrate the extremes that can be obtained (see for example Hoogwijk et al. (2003)). The studies also describe a range of potentials (theoretical, technical and economic) that are inconsistently defined

Figure 4.1: Biomass potential forecasts by individual study and timeframe.

(NB: figures are those reported in the original study and incorporate different definitions of potential (theoretical, technical, economic, etc.); studies also differ in terms of the range of resources included.)

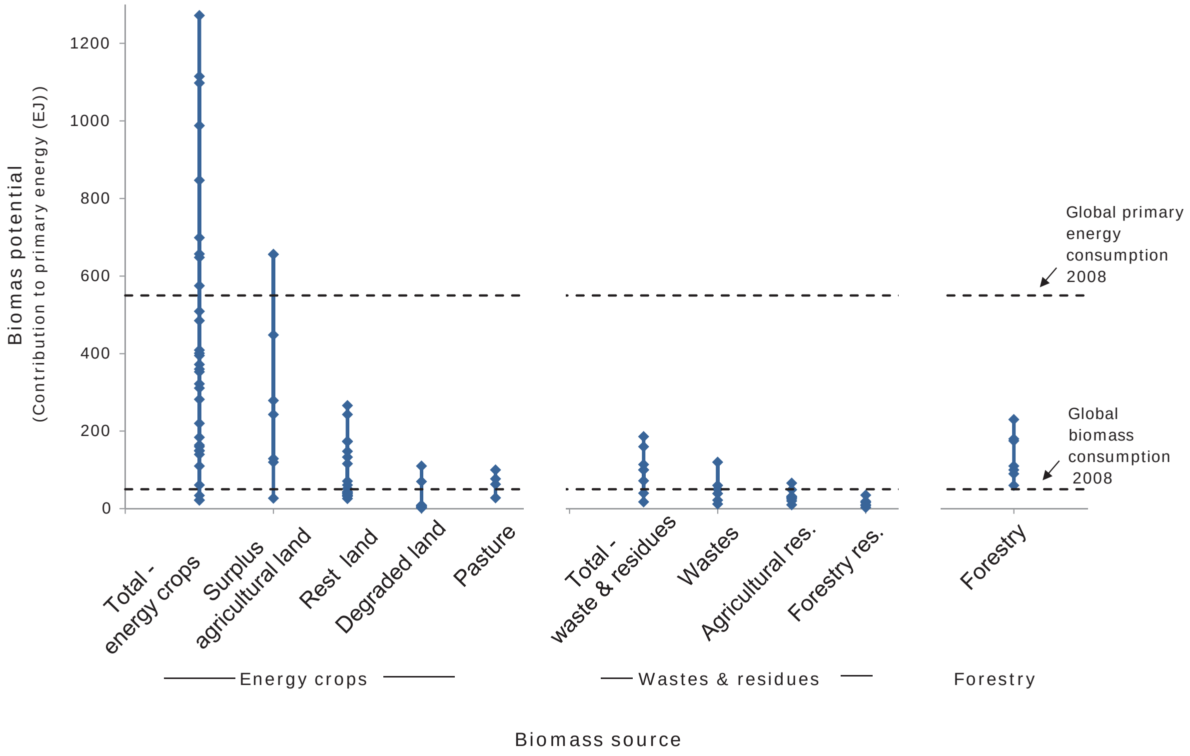


and thus not directly comparable; they also differ in terms of the range of feedstocks included. Nevertheless, on a more qualitative basis, it is interesting to note that more than half of the predicted values for 2050 fall between 50 and 300 EJ.

The relative contribution to biomass potentials from the different categories of biomass is described in Figure 4.2. This figure requires cautious interpretation because land use categories are not consistently defined across studies and cannot be considered mutually exclusive. Estimates (and totals) for energy crops, wastes & residues, and forestry also include unconstrained values. Nevertheless, it can be seen that the greatest potential contribution comes from energy crops, grown on a variety of land types, the most important (and controversial) of which being agricultural land. While it is evident that the potential contribution from wastes, residues and forestry are far less than many estimates for energy crops, these potentials also appear significant compared to total global energy consumption.

Land use categories are not consistently defined or mutually exclusive. Estimates (and totals) 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* is also defined as *low productivity* or *marginal* land in some studies. *Waste* includes dung, municipal solid waste and industrial waste. *Forestry* describes harvest of a fraction of the annual growth increment.

Figure 4.2: Indicative contributions to global biomass potential estimates from different biomass sources and land classes

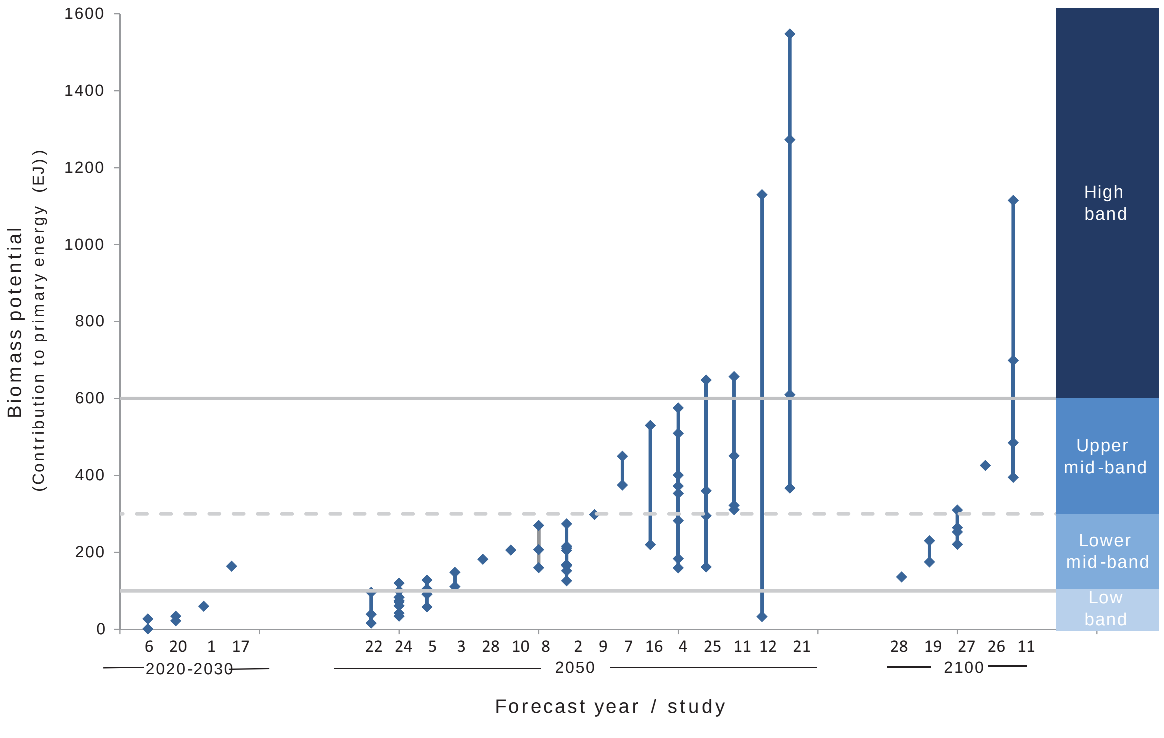


4.1 What assumptions lead to high, medium or low estimates?

More detailed investigation into the assumptions that underpin the studies can most sensibly be achieved by normalising estimates to the amount of primary energy contained in the biomass[25]. The results of this normalisation are shown in Figure 4.3.[26]

Because we are primarily interested in understanding the assumptions that underpin similar estimates, the data have been analysed in terms of three bands: *high, middle* and *low*. The *low* band (0-100EJ) represents values less than 10% of the maximum anticipated primary energy demand in 2050. At this level, future biomass supply would be comparable to (or less than) the contribution that biomass makes to primary energy supply today (50-70EJ) (IEA, 2008). 100EJ is also

Figure 4.3: Biomass potential forecasts normalised to consistent definition of technical potential (primary energy content of biomass)



1 -Bauen04
2 -Beringer11
3 -Cannell02
4 -deVries07
5 -Erb09
6 -Field08
7 -Fischer01
8 -Haberl10
9 -Hall93
10 -Johansson93
11 -Hoogwijk05
12 -Hookwijk03
13 -Hoogwijk04
14 -IEA08
15 - IEA10
16 -Lysen08
17 -Moreira06
18 -OECD/FAO08
19 -Rotiyanskiy07
20 -Sims06
21 -Smeets07
22 -Thrän10
23 -WEA00
24 -WGBU09
25 -Wolf03
26 -Yamamoto99
27 -Yamamoto00
28 -Yamamoto01

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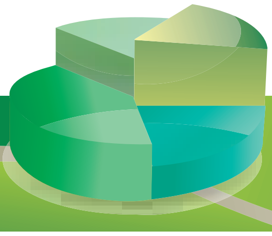
[25] To do this, economic potential estimates and estimates including conversion losses were converted back to a technical potential (primary energy) using the conversion efficiencies specified in the original paper. In fact, the only paper that requires this is the deVries07 study. The Hookwijk04's technical potential estimates are contained in Hookwijk05 study. In other cases, estimates of technical potential are a subset of the figures described in each paper. This normalisation process does not affect the sustainability criteria used in each study. Demand estimates are excluded from this analysis.

[26] It is noticeable that for a number of studies (Bauen04, Canell02, Fischer01) normalisation collapses the range of estimates. This is because the original study described a more limited range of biomass potentials and then overlaid these with scenarios describing alternative constraints.



the IPCC's estimate for "low" biomass deployment in 2050 (IPCC, 2011).

The *middle* band (100-600EJ) represents values from 10 to 60% of the maximum primary energy supply in 2050. The upper bound for this band is chosen simply so that this band contains over half of the 2050 forecasts. It should be noted that 600 EJ is an amount of energy that exceeds global primary energy consumption in 2010. To help differentiate studies further, this band is further subdivided at 300EJ. 300EJ is the IPCC's estimate for "high" biomass deployment in 2050.

The *high* band (>600EJ) represents very large potential estimates at between 60-150% of the maximum anticipated primary energy supply in 2050.

The remainder of this chapter considers each of these bands in turn starting with the *low* and *high* bands. The chapter concludes with a summary of the most important assumptions. The data for each study is described in Annex 3.

4.2 Low Band Estimates (<100EJ)

The *low-band* estimates in the 2000-2030 forecast period focus primarily on energy crops. Either a comparatively small area of agricultural land is assumed to be available (<0.15Gha) and anticipated yields are modest (8-12odt.ha^{-1}.yr^{-1}), or a somewhat larger area of marginal land (<0.4Gha^{-1}) is available but is anticipated to give very low yields. Improvements in crop productivity are not considered. More limited variation arises from the inclusion (or exclusion) of biomass from residues and wastes (+/- 17EJ).

Low-band estimates for 2050 all assume that there is little or no land available for energy crops owing to the demands of food production. They also assume affluent diets across the globe and low agricultural yield figures, mainly driven by low external inputs to agriculture (water and fertiliser), whether through a rise in organic production or through the use of marginal land. The contribution from wastes and residues is not considered in all studies, but where included the net contribution is in the range 28-30EJ.

4.2.1 Low-band 2000-2030

Four studies fall within the 2000-2030 period; three in the low band: Field08, Sims06, and Bauen04; and one just outside: Moreira06.

The Field08 study considers a low yielding energy crop grown on an area of abandoned cropland (0.386Gha; 3.5odt.ha^{-1}) identified using land cover maps and satellite imaging data. This is a simple but rigorous methodology and results in an estimate of 27EJ.yr^{-1}. The main criticism levied at this study is that the scope is limited because it only considers a single land class (Haberl, et al., 2010).

The Sims06 study, in contrast, is more basic and simply takes a global land area estimate from the literature (IPCC, 2000) and multiplies this by yield estimates for energy crops (willow) grown in Scotland and assumed to be broadly indicative of the anticipate range of global yields (0.141Gha; 4-12odt.ha^{-1}). The results are comparable to Field08 because, although the area assumed is smaller, the yields assumed are larger.

The Bauen04 study is an archetypal rule-based, bottom-up resource assessment. The energy crop estimate (42.5EJ), is very similar to the previous two studies but the derivation is different: the study assumes that 5% of global cropland, grassland and forestry land area will be available (0.283Gha; ~8odt.ha^{-1} [27]). The rationale for this is historic levels of overproduction in the OECD. In addition to energy crops an estimate for residues and wastes (17.4EJ) is also included.

Although it falls outside of our defined *low* band, it is interesting to contrast the Moreira06 study with the other studies in the 2000-2030 period. This study considers energy crops grown on a land area almost identical to that considered by Sims06, but describes a potential almost three times greater (0.143Gha, unexploited rainfed land in South America and Africa). The reason for the difference is that the author of this report stipulates that the land will be located in the tropics and will be used to grow sugar-cane. The authors assume this will yield ~60odt.ha^{-1}, a value that is close to the maximum yield ever recorded in irrigated field trials and close to twice the global average. Unlike the other studies in this period, Moreira (2006) incorporate predicted increases in productivity due to technological improvements. It is interesting, therefore, to compare these figures with existing production. In 2009, the global sugar cane area was ~23Mha and yielded ~35odt.ha^{-1} (70t.ha^{-1} fresh weight). Increasing the area to 143Mha by 2030 would require expansion at the rate of ~6Mha per year. This would be equivalent to planting an area the size of the UK every 4 years. Between 1999 and 2009 the area of sugarcane harvested in Brazil, the world's largest producer, increased by 3.6Mha (FAOSTAT). It is evident from this comparison that the estimates by Moreira (2006) are rather ambitious. It will be seen later in this report that the rate of technological improvement is one of the key factors that differentiates between studies in each of the bands.

4.2.2 Low Band 2050

Four studies contain estimates that fall predominantly within this low (0-100EJ) band: Thran10, WGBU09, Erb09, and Hookwijk03. All the studies include energy crops, but only Erb09 and Hoogwijk03 include contributions from agricultural residues, (Hoogwijk03 also includes forest residues and wastes).

The earliest of these studies, Hoogwijk03, stands out from the others as it produces both one of the lowest (33EJ) and the highest (1130EJ) estimates. The study is essentially a re-appraisal of earlier literature estimates for residues and wastes combined with an assessment of how much good quality agricultural land might become available under alternative scenarios (for population growth and dietary change). The study purposefully adopts extreme scenarios in order to expose the relative importance of underlying assumptions.

The discussion of land use change is limited to the 5Gha of agricultural land that is used globally for crops and pasture. Constraints on the amount of land available for energy crops include a 'safety factor of two' on the area required for food

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[27] The Bauen04 study assumes 150GJ.ha^{-1} or 10adt.ha^{-1}. this corresponds to ~ 8odt.ha^{-1} assuming the calorific value of wood is 18.5GJ.odt^{-1}

production. If low-input agriculture is assumed, in combination with a moderate or affluent diet – as is the case in the *low-band* estimate – the land available for energy crops is zero. Conversely, if a vegetarian diet is assumed in combination with a high-input agricultural system and rapid rates of technological improvement, the land available for energy plantation increases to 3.7 Gha – an area more than twice the global arable area and nearly ten times the size of India. Interestingly, changes in population are proportionately less important than diet and the level of agricultural intensification.

In addition to these scenarios for the availability of agricultural land, Hoogwijk et al. (2003) assume an area of low productivity degraded land will be available providing ~8EJ per year (0.43Gha; 1odt.ha^{-1}). This is added to an estimate for residues and wastes (net 25EJ)[28] to give a combined 'minimum' figure for the global biomass potential using no agricultural land (33EJ). Somewhat counter intuitively, this *minimum* figure for the biomass potential includes *maximum* estimates for waste and residue recovery.

Thus the major driver behind Hoogwijk03 *low-band* estimate is the absence of any good quality land available for energy crops, which, in turn, is driven by assumptions of high food demand and low productivity, low input, farming. These low values are combined, however, with very optimistic estimates for residue recovery. It is also worth considering, as noted by the same authors in subsequent work (Hoogwijk05), that recovering biomass from low yielding degraded land may not be practical or economic.

The analysis presented in the Thrän10 study is a similar re-appraisal of literature estimates and applies scenarios for rates of change in population, yields, land use, and deforestation; food consumption and organic farming. Unlike Hoogwijk03, however, only energy crops are considered. The lowest estimate (16 EJ) is driven by decisions not to convert forest or grassland into cropland along with limited use of fallow land for energy. Thrän et al.'s mid-range estimate (39EJ) is interesting because it describes a higher biomass potential but applies even greater limits on land use by assuming a large increase in organic farming which in turn limits yield growth. The explanation is that this scenario also puts a constraint on food consumption within countries eating more than the WHO recommended level (USA, Canada, EU, Australia): the assumption is that meat, sugar and fat consumption (which take large areas of land to supply) will decrease by as much as 30% by 2050. Thrän et al's upper estimate (96EJ) is a business as usual scenario and permits grassland conversion (0.1%pa) and deforestation (0.24%pa) but excludes the use of fallow land.

Estimates in the Erb09 study are derived from a spatially resolved database of global land use, overlaid with productivity maps showing net primary productivity (NPP). This model is interrogated using scenarios that vary diet, pace of land use change, livestock farming intensity and

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[28] Primary and secondary agricultural residues contribute 32EJ (25% recovery), forest residues: 16EJ; animal residues: 25EJ (assuming 25% dung recovery and 1% pa growth in animal numbers); MSW: 3EJ (assuming 75% recovery and 0.3 tonne per capita per year production). Demand for biomaterials is 83EJ of which 32EJ is subsequently available for energy purposes as industrial residues. The net availability of residues for energy use is thus 25EJ.

food agriculture intensity. Two of their four estimates fall in the *low-band* (58EJ; 91EJ), and two just outside (105EJ; 128EJ).

Their results show that if a high protein western diet was adopted across the world, it would only be possible to free up agricultural land for bio-energy production if highly intensive livestock and arable farming were adopted. In this study “highly intensive” production describes industrial and landless production of pigs and poultry and increased use of fertilizers, herbicides and pesticides for arable farming. Even then, in order to generate 58 EJ of biomass would require land use change the authors describe as “massive” (the area is not stated in the study, but we estimate that this scenario would require ~200Mha). If diet were steered slightly away from the western extreme, to a more “current trend” scenario, then less intensive agricultural management options are possible; nevertheless, the adoption of low intensity organic agriculture on a large scale would still most likely be prohibited. Under these more optimistic dietary assumptions, Erb et al. (2009) estimate that up to 91EJ of biomass might be generated from spare agricultural land and crop residues. Once again, diet has a much larger influence on the biomass potential than any of the other factors: a shift in global diet from one extreme scenario to the other changes the biomass potential from energy crops by a multiple of ~3.5. All the other factors put together generate only a doubling of biomass potential: i.e. moving from wholly organic farming and livestock rearing and “business as usual” land use change to intensive farming, livestock management and “massive” land use change. Consequently, both upper estimates (105EJ; 128EJ), require meat consumption to be reduced.

The WGBU08 report is arguably the most comprehensive study of the implications of growing bio-energy crops considered here. The approach uses a spatially explicit yield model for terrestrial productivity (LPjmL) driven by IPCC climate models, and scenarios. The model is able to estimate the productivity of different crop types in different areas (although at a highly aggregate level). It is applied to the global land area after land exclusions have been identified; these include existing farmland, and marginal soils. Interestingly, the results are similar to the Erb09 study which aims to identify representative values for NPP.

The study develops four scenarios for land availability: assuming either high/low levels of nature conservation and high/low demand for agricultural land. A further scenario where up to 10% of energy crop land is irrigated is also considered. Compared to other assessments this study stipulates a high degree of nature conservation. It also assumes that no land presently used for food production will become available for energy crop cultivation. The land available (0.24-0.5Gha; 34-120EJ) is thus predominately located in marginal areas. The authors also identify a number of reasons why the model results might represent an overestimate. These include the fact that competition for water is not considered and the fact that land identified as “unused and available” is in actual fact being used for fuelwood collection and to graze livestock.

4.3 High Band Estimates (>600EJ)

At the other end of the spectrum, *high band* estimates describe a range of extreme scenarios where far less land is needed for food production. These can only be achieved with a combined *low-food-demand and high-biomass-supply* vision of the future. Low food demand can be the result of either a largely vegetarian global diet or low global population; high biomass (food and energy) supply can either be achieved with high agricultural inputs and rapid technology driven yield increases, or with the large scale expansion of agriculture into forested areas. None of the authors suggest that estimates in this band describe an appealing prospect for delivering biomass in the future, rather their purpose is to describe theoretical upper limits on what could be achieved, and to make relationships and trade-offs explicit.

The four studies describing biomass potential estimates over 600EJ are Hoogwijk03, Wolf03; Hoogwijk05, and Smeets07. The first two of these also produce results in the low band under some scenarios, consistent with their aim to explore the range of influence of key assumptions.

The Hoogwijk03 study, is also described in §4.2.3 above. The high-band estimate (1130EJ) is intended to be an extreme value, and assumes that over half the global agricultural area[29] is dedicated to energy crops. This is only possible with the assumption that the global diet is largely vegetarian and that energy crop and food yields are the best technically achievable. Interestingly, this high estimate includes low estimates for total residue use (32EJ), presumably on the basis that residue production decreases as crop production intensifies.

The Wolf03 study pre-dates Hoogwijk03 but the approach is similar: land availability is modelled using alternative scenarios for population, diet and agricultural intensification. The high-band estimate necessitates a largely vegetarian global diet requiring less than a third of the land area needed to support an affluent diet. High external input levels to agriculture that maximise production up to the best technical means are also assumed. The yield for energy crops is based on rainfed grassland yields with high external inputs (fertilizer) but is relatively conservative (7.3odt.ha^{-1}) – at least in comparison to the 18odt.ha^{-1} assumed by Smeets et al. (2007). The Wolf03 *high band* forecast (648EJ) derives from the assumption that an area equal to the total existing global agricultural area (5Gha) is used for energy crops. This is only possible with extensive deforestation and conversion of grassland. The authors note that "such a drastic change in land use might not be acceptable".

The estimates in Wolf03 that fall below the high band correspond to scenarios for more affluent diets, less intensive agriculture, and limited land conversion. Notably a high food demand, low technological improvement scenario can result in a zero estimate for energy crops.

The Smeets07 study describes two scenarios that posit huge energy potentials from biomass (1548EJ and 1273EJ). These values can be judged as

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[29] 2.6Gha out of a maximum 5Gha

the ultimate high value for the technical biomass potential where everything is included as optimistically as possible, and without any sustainability or practicality constraints. The major part of the energy potential (>80%) comes from energy crops with the remainder from residues and wood products (including harvest from natural forests) which contribute of the order of 100 and 180EJ respectively.

The assumptions for food production in these scenarios are based on very high productivity estimates using genetic modification, irrigation and high external inputs (also included is an assumed positive contribution from the fertilization effect of higher atmospheric carbon dioxide concentrations)[30]. This combination releases up to 70% of current agricultural land for energy crop production. This land use assumption meets the needs of food production but there is no safety margin: i.e. the land available for food exactly equals the amount of food required. All other land, including that graded as not suitable for agriculture, is used for biomass production.[31]

While not explicit in the study, it appears that all land is assumed to be used without any reduction for inaccessibility or unsuitability. It is also assumed that the gross annual forest growth increment is harvested, effectively transforming all mature forests into managed forests (although in this case some reduction for physically inaccessible areas is assumed). The energy crop yield assumptions are also high, considering that much of the land allocated to energy crops is graded as "the least productive" and "not suitable for conventional commercial crop production".

The Hoogwijk05 study uses the integrated model IMAGE in combination with the four IPCC SRES scenarios to forecast land use in 2050 based on population and diet needs. This approach identifies "surplus" land that can then be allocated to energy crops. Spatially explicit yields are also predicted by the model based on the level of technology advancement assumed under each scenario. Estimates for residues are not included.

In 2050, one of the four scenarios appears in the high band (scenario *A1*; 657EJ), but by 2100 this has increased to two of the four scenarios (Scenario *A1* 1115EJ; and *B1*, 699EJ). Because the IPCC scenarios vary many attributes at the same time, it is difficult to unpick exactly which factor is causing which effect, yet the combination of factors is broadly similar to other high band estimates. The *A1* scenario, for instance, describes a future world in which population growth is relatively low (8.7bn in 2050 decreasing to 7.1bn in 2100), and this, in combination with rapidly improving food crop yields (up to 82% of the optimum yield on each land class) releases large areas of land. The productivity of the energy crops grown on this land also doubles in the period up to 2050 as a result of improved management and fertilisation (1.6%pa increase[32]). Realising these food and energy crop yield gains

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[30] These improvements are described in terms of a management factor that results in yields in 2050 being 1.5 x yields in 1995.

[31] In Smeets07 the average energy crop yield estimates for woody crops on "surplus agricultural land" in 2050 range from 16-21odt.ha^{-1}.yr^{-1}.

[32] The improvement in crop yields is expressed in terms of a "Management Factor". This factor describes yield as a fraction of the best rain-fed yield achievable under optimal conditions. The initial management factor was estimated for each grid square from 1995 crop yields and permitted to increase up to a maximum value. For energy crops in the A1 scenario it is assumed that the initial management factor was 0.7 in 1995 increasing to 1.5 in 2050: i.e. an increase of ~2.1 times.

implies biotechnological improvements in addition to optimal fertilisation. A vast area of "rest land[33]" is also dedicated to energy crops in the *A1* scenario (~1.1Gha; around 9% of the global area). Although this scenario describes a high meat diet, this is compensated for by a small population, rapid yield increases, and very large areas dedicated to energy crops. The difference between 2050 and 2100 simply illustrates what happens when yield increases are modelled to continue for another 50 years.

The *B1* scenario is similar except that it is assumed that energy crops on "rest land" are limited for environmental reasons. Consequently, this scenario does not appear in the upper band until 2100 when cumulative increases in agricultural yields release more land from agricultural production.

The other scenarios analysed in Hoogwijk05 fall below the high band in both 2050 and 2100 but it is nonetheless useful to consider them here for comparison. The *A2* scenario (311/395EJ in 2050/2100) is characterised by high population and meat consumption which results in high land demand for food production. This is combined with lower rates of technological improvement and consequently less agricultural (0.6 /1.2Gha in 2050/2100, ~11odt.ha^{-1}) and "rest" (1.25Gha, ~8odt.ha^{-1}) land becomes available for energy crops. This scenario also leads to extensive deforestation (0,7Gha ~twice the size of India) in order to meet demand for food.

The *B2* scenario (322/485EJ in 2050/2100) provides similar figures for biomass production as the A2 scenario and has similarly low rates of technological improvement, but food demand is less owing to a smaller population and a substantially vegetarian diet. This allows the biomass-for-energy to be produced on "abandoned" agricultural land and deforestation is avoided.

Hoogwijk et al. (2005) note that all these scenarios are "extreme and theoretical". They caution against simply assuming that the potential for all the land classes they describe could be implemented because it would imply 30-40% of the total global land area would be dedicated to bio-energy production.

4.4 Mid Band Analysis

Having found that extreme high and low estimates are principally driven by radically different assumptions about the extent and intensity of food and energy crop production, we now turn our attention to the estimates that fall predominantly within the mid band. Similar to the analysis presented above, the intention here is to assess whether there are any common themes in the lower and upper end of these forecasts. A second objective is to ask whether there are any obvious break points in the data where a fundamental shift in assumptions is necessary in moving from lower to higher end. To do this we take two approaches; firstly we choose studies that appear entirely in the lower end of the mid band (between 100 and 300EJ) and compare them with studies that appear entirely in the higher end of the mid-band

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[33] Hoogwijk et al. (2005) define *rest land* as savannah, extensive grassland and shrub land. The proportion of this area used for energy crops is not entirely clear, but appears to be ~50% of 2.3Gha in 2050 in the *A1* scenario and 10% of this area in the *B1* scenario.

(400 to 600EJ). Secondly, we choose studies that produce a range of results right across the band and investigate what drives that range.

4.4.1 Lower – mid band (100-300EJ)

The studies that occur in the lower mid-band assume 26-230EJ from energy crops. These would be produced on 0.1-0.5Gha yielding ~10-20odt.ha^{-1} (0.1 Gha is equivalent to the combined area of France and Germany. 0.5Gha is half the size of China).

Yields of food crops keep pace with population growth and increased meat demand, but no "surplus" agricultural land is generated for energy crop production. Consequently, most of the land for energy crops comprises marginal and degraded land in developing countries. A decrease in the global forested area (up to 25%), or replacement of mature forest with young growing forest may also be required if food demand is high. A contribution from residues is also included in most assessments (60-120EJ)[34].

Four studies fall clearly into the lower-mid-band and merit discussion[35]: Beringer11, Johansson93, Yamamoto01 and Rotiyanskiy07. Notably, each study adopts a different approach.

The analysis presented in the Beringer11 study is closely related to the work presented in the WGBU08 report. It uses the same model for terrestrial productivity (LPJmL) (see §3.3), and very similar assumption: i.e. that no existing pasture or cropland is converted to produce energy crops. The biomass plantations would therefore be located on natural grasslands and shrublands (40%), and forested areas (30%). Pristine forested areas (e.g. the amazon), areas of high biodiversity, and areas where simulated carbon losses after land use change are not compensated for by subsequent biomass yields within 10 years are excluded. The main difference is the use of updated land area scenarios (0.142-0.452Gha^{-1}, giving a potential of 126-274EJ) which include a larger number of exclusions, and the addition of a greater number of modelled crop types – some of which have increased yields. A combined estimate for residues and wastes (100EJ) is also added to all scenarios.

Although this study is not premised on yield improvements making agricultural land available, the authors note that constraining future food supply to the existing agricultural area necessitates a 1.2% year on year increase in crop yields simply to keep pace with population growth. Interestingly, this study also shows that a scenario in which 10% of energy crops are irrigated could almost double the energy crop yield (from 26-116EJ to 52-174EJ) but would consume a quantity of water comparable to the amount already used for agricultural irrigation, (which the authors consider unlikely). Another noteworthy facet of the discussion is that the rates of land-use

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[34] This range assumes the contribution of residues is limited to the recoverable fraction.

[35] Cannell's analysis is not considered further. It simply derives a land use estimate from literature (800-600Mha) and multiplies by a yield of 10odt.ha^{-1}. This approach cannot be expected to give anything more than an indicative result. The Haberl10 study is principally a synthesis of earlier studies. It is of some interest because it is one of the few studies to include a detailed review of estimates for agricultural and forestry residues and wastes. Caution is required however, as the dataset for residue availability is limited and extensively extrapolated.

change needed would be twice the rate of agricultural expansion over the last 40 years.

The Johansson93 study is an archetypal rule based and resource focussed assessment that postulates a biomass potential of 205EJ: 128EJ from energy crops and 77EJ from residues, and forestry. It is primarily interesting because it is one of the earlier reports and has been cited in much of the subsequent literature either as a source of model parameters or as a point of comparison (see for example Hoogwick03, Yamamoto et al., 1999, 2000, 2001, Berndes, et al., 2003).

The study provides a comprehensive inventory of potential biomass feedstocks[36] by applying simple rules to global data sets. For example, forestry residues are estimated from the FAO's industrial round wood production figures for 1985 using the following rules: i) that total production would increase in line with population; ii) that 45% of the harvested wood would end up as mill residues (of which 75% could be recovered for energy purposes); iii) that harvest residues normally left in the forest could also be collected (forest residues were estimated to be 0.39 times round wood production, 50% of which was assumed to be recoverable). These fractions were applied globally, but were derived from literature on forestry production in the United States in the late 1970's; consequently, the resulting estimates must be interpreted with caution. A similar approach was adopted for other feedstock categories.

For energy crops it was assumed that 429Mha of land was available (mostly marginal land in Africa and South America), yielding 15odt.ha^{-1}.

The Yamamoto01 study uses an integrated model of global land use and energy (GLUE)[37]. This model describes how regional population and GDP forecasts drive competition for land between different sectors (including paper, timber, food, feed, and energy). The allocation of land to bio-energy is determined by this competition, but the basic availability of resources (i.e. land and residues) is taken from Johansson93 and other literature sources[38]. The results of the model are that energy crops could provide 110EJ in 2050, but this decreases to 22EJ in 2100, because food demand grows faster than crop yields. At the same time, however, the contribution from residues increases as the population grows and consumes more. The area of forested land is not permitted to change, but increasing demand for forest products mean that by 2100 a quarter of the global mature forested area has been harvested and re-afforested – i.e. natural forest becomes managed forest) . Land use for energy crops is not explicit but appears to lie in the range 79-396Mha, consistent with other estimates in the *lower mid-band*[39].

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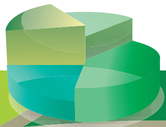
[36] Forestry, forestry residues, energy crops, cereal and sugar cane residues, urban refuse and dung.

[37] The GLUE model is based on an integrated modelling approach developed by Edmonds & Reilly (1983). This approach also underpins the integrated model GCAM (formerly MINICAM) which has been used to develop IPCC scenarios. http://www.globalchange.umd.edu/models/gcam/

[38] Yamamoto's 2000 and 1999 studies are simpler versions of the same model. They result in higher estimates for the amount of biomass available, because crop yield growth is greater and no recoverability constraints are applied to residues.

[39] It is assumed in this study that up to 619Mha of fallow, degraded and semi desert land could be available for arable and /or energy crop use. Berndes (2003) has criticised the land use assumptions built into the GLUE model, noting that they imply deforestation and double counting of cropland.



The Rotiyanskiy07 study uses an integrated, profit maximising economic model (DIMA) to estimate future areas of afforestation and avoided deforestation under exponentially increasing carbon price scenarios. The areas where afforestation is permitted are constrained to allow adequate space for food production and urban development, but detailed assumptions are not explicit. This study focuses primarily on carbon sequestration and the information it provides about the future potential of biomass is somewhat opaque; nonetheless, it appears to describe a scenario for 2100 that assumes that ~175-230EJ can be produced from ~500-610Mha of land. Most of this land (~70%) would come from avoided deforestation, and would be located in the tropics (~70%). It is not clear how avoided deforestation equates to availability for biomass production, and seems to imply that natural forest becomes managed forest, i.e. mature forest would be harvested and then re-afforested in a long rotation. Like the study by Erb et al. (2009), yields are region specific estimates of NPP[40], the overall average yield, however, is ~20odt.ha^{-1}.

4.4.2 Upper mid-band (300-600EJ) and cross cutting studies

Turning our attention to studies that only feature in the *upper mid-band*, the studies by Fischer01 and Lysen08 are the obvious candidates for further analysis. Looking also at studies that predict potential right across the mid band, the WEA00 and deVries07 forecasts also merit discussion.

The feature these studies have in common that distinguishes them from studies in the lower mid-band is that they all assume energy crops will be grown on very large areas of land (>1Gha). This is made possible by the assumption that increases in food-crop yields will outpace demand for food, with the result that high yielding agricultural land will be available for energy crops.

The Fischer01 and Lysen08 studies also provide very complete inventories of bio-energy feedstocks; both including managed forestry, which many studies choose to exclude as unsustainable because of the potential impact on biodiversity. These studies also assume that a high level of residue and waste recovery is possible.

The Fischer01 study compiles a comprehensive inventory of feedstocks, including energy crops (140/220EJ), agricultural residues (20EJ), wastes (120EJ) and forestry to give a combined total potential of 370-450EJ. The study classifies land into four categories: *arable, grassland, forests* and *other*[41], and uses a scenario developed by IIASA (BLS-BAU) to describe how the size of these land categories may change over time. The arable area is all used to produce food and is assumed to expand by 280Mha by 2050 – at the expense of grassland and forests. This comparatively small increase is made possible by the assumption that food crop yields will increase at ~1.1%pa. Energy production is assumed to occur on the remaining grassland and forest areas. It is assumed that no land classified as *other* will be used.

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[40] Calculated using global vegetation model called TsuBiMo. The spatial resolution of the model is a 0.5° grid.

[41] The Fischer01 definition of other land includes urban areas, protected areas, barren land and deserts.

Energy crops grown on grassland and pasture contribute ~140-220EJ. These crops require an area of 1.9-2.3Gha. This is between 60-75% of the total global grassland and pasture area and corresponds to an area about double the size of China. Yields were estimated using the FAO's agro-ecological zones methodology[42], with the addition of a 1%pa yield improvement. The global average yield in 2050, however, is comparatively low (70GJ.ha^{-1} or ~3-4odt.ha^{-1}), and even in Pacific Asia and Eastern Europe, the highest yielding areas for grassland, the expected yield attained in 2050 is only around 200 GJ.ha^{-1}, or about 10odt.ha^{-1} per year.

The use of so much grassland for energy crops implies that the majority of livestock will be produced in feedlots. This allows the dung to be collected and used for energy (~60EJ.yr^{-1}). The other source of wastes is municipal solid waste, this is estimated on a per capita basis, and it is assumed that around half (~60EJ.yr^{-1}) of all MSW is recovered for energy purposes. These estimates for wastes and residues are high but of the same order of magnitude as the studies appearing in the *lower mid-band*.

Forestry contributes ~100EJ.yr^{-1}. The assumptions about how this figure is derived are not explicit, but it appears that the entire global forest area (3870Mha) is available for managed production of energy, limited by regionally specific accessibility fractions[43]. A 1%pa increase is also assumed – but it is not clear whether this is an increase in yield or accessibility.

The principal reason this study appears in the *upper mid-band*, therefore, is the large areas of grassland and forestry dedicated to bio-energy production.

The Lysen08 report repeats the analysis undertaken by Hoogwijk et al. (2004, 2005) using the same IMAGE model, but applying an alternative scenario (OECD DV-2) that describes a medium-development future with a 9.4bn population in 2050 and annual per-capita growth in GDP of 2%. They also test the sensitivity of the results with additional constraints for degraded and water-stressed land. The resulting biomass potential ranges from 290-530EJ.

Similar to the Hoogwijk05 study, improving food crop yields free-up large areas of land for energy crops (120EJ). The rate of improvement is lower[44] than the Hoogwijk05 *high-band* (A1) scenario but it is implicit that the area of abandoned agricultural and grassland will be of a similar order of magnitude (~1Gha). To test the sensitivity of the model to the assumed rate of yield improvement the authors calculate that if yields of all crops in all regions were to increase 12.5% over 1990 levels due to technological learning (in addition to the 1.4%pa increase), this could add 140EJ to the total.

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[42] The authors use of the FAO agro-ecological zone model produces values lower than other models, for example the IPCC's estimates, which is acknowledged by the authors.

[43] The fraction of forests available and accessible was taken from a report in German by (Dessus, et al., 1992). Berndes et al, (2003) describe this report and note that the availability fraction stated was 50-70%, and the accessibility fraction: 25-80%.

[44] It is not possible to compare the rates of growth in these two papers directly. Hoogwijk05 assumes that agricultural yields increase to 82% of optimal by 2050, but the initial yield is not stated. Lysen08 use estimates from the FAO (FAO, 2003); a figure is not stated explicitly in the paper but the global average figure from this reference is 1.4%pa, implying a ~50% increase in food yields between 2000 and 2050.

Energy crops grown on an area of degraded, water scarce and marginal land provides an extra 70EJ. Again the area and yields are not specified, but if the yield were consistent with Hoogwijk et al.'s (2005) productivity estimate for "low productive areas" (3t.ha^{-1}) this would imply an area of ~1.3Gha.

Lastly, residues and "surplus" forestry are also added, contributing 100 EJ and 60-100 EJ respectively. This figure for forestry appears to come from Smeets07, and so implies that the entire accessible forest area is extensively managed and the gross annual growth increment harvested. The accessibility fractions used are not explicit. It might also be argued that describing this biomass as "surplus" does not accurately communicate the risks involved in making this biomass available.

Diet and food demand is not investigated in any detail and the authors acknowledge that is a large uncertainty in estimating potentials, alongside accurate yield assumptions.

The deVries07 study focuses on calculating economic potentials for electricity and transport fuels based on the IPCC SRES scenarios (*A1, A2, B1, B2*). The resulting biomass potential ranges from 160-575EJ. Once again, the methodology is essentially the same as that applied in Hoogwijk05 and uses the same rates of technological improvement. The principal difference is that greater constraints are placed on the use of extensive grassland, scrubland and savannah[45].

Having normalised the data to primary energy contained in the biomass, we find that the biomass potential ranges from 160-184EJ in the case of the A2 scenario (high population, high meat diet and low technology development) to 401-575EJ in the A1 scenario (low population, high meat diet and high technology development). This kind of scenario study, while being able to model complex future circumstances makes analysis of individual effects impossible. Similar to the Hoogwijk05 study, we should conclude that the range is driven by the amount of land available, which in turn depends on demand for food and the rate of improvement in crop yields.

The analysis undertaken for the World Energy Assessment (WEA00) in contrast is a straightforward bottom-up calculation. This assumes a land area of 1.28Gha and multiplies this by high/ low yield estimates (15/8.5odt.ha^{-1}) to give a potential range of 276-446EJ. This range includes traditional biomass (50EJ). The area estimate comes from FAO's 1995 forecasts of land use and land availability (Alexandratos, 1995) and assumes expansion of modern farming methods can increase crop yields to keep pace with population growth. The vast majority of this land (~90%) is located in Africa and South America and includes deforested and degraded areas.

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[45] Extensive grassland, scrubland and savannah correspond to Hoogwijk05's definition of "rest land". The proportion deemed available by de Vries et al., (2007) is default 20% (min10%, max 25%). This compares to Hoogwijk et al.'s (2005) assumption that ~50% might be used. de Vries et al., (2007) also apply greater constraints to the amount of low productivity land that may be used (default 10%, min 5%, max 20%) but this makes little difference to the result because the yield for this land class is negligible.

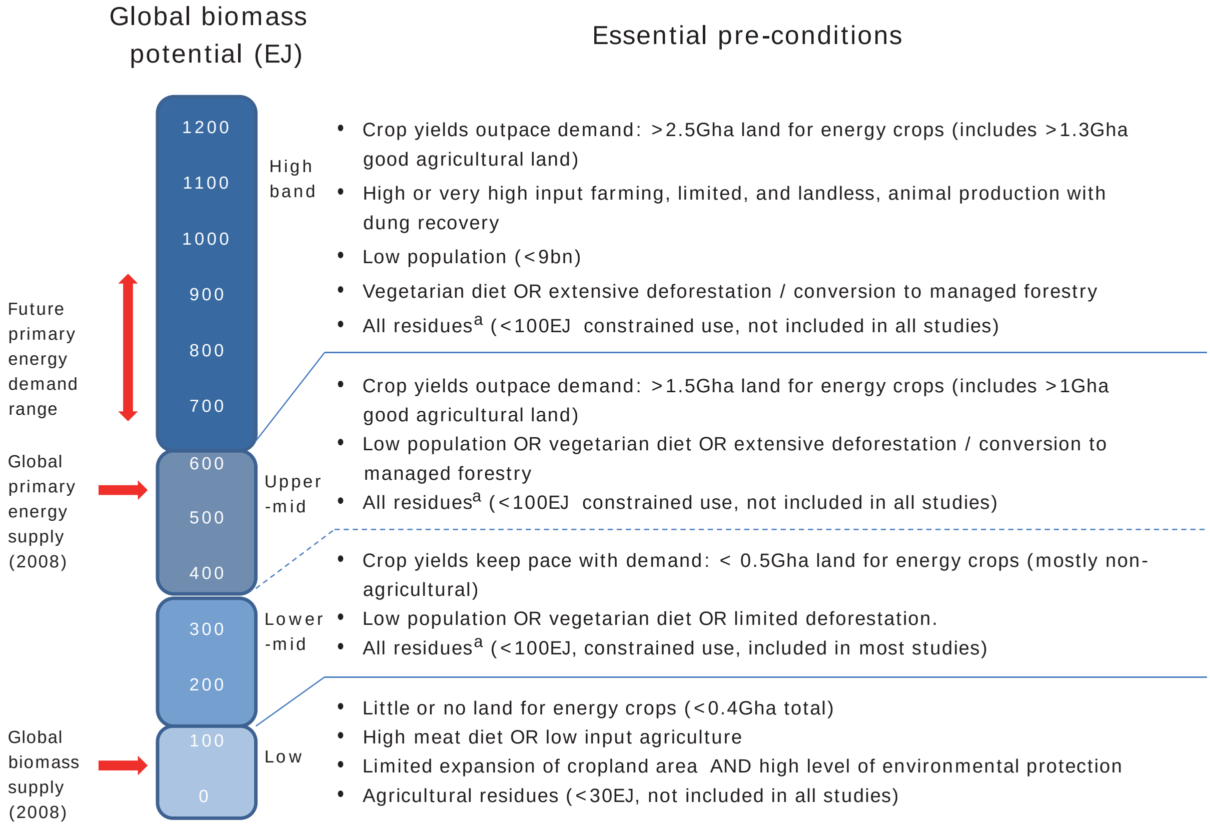
4.5 Summary

This chapter examines the assumptions that underpin estimates of future biomass production and potential contribution to global primary energy supply. All the studies reviewed here examine the potential contribution from energy crops, but the contribution from residues and wastes is only considered in a subset of the studies, and typically in less detail. Estimates are considered in terms of three bands: *Low* (0-100EJ), *High* (>600EJ), and *Medium* (100-600EJ). The *Medium* band is further divided into an upper and lower region to further differentiate key studies. The assumptions which underpin each of these categories are summarised in Figure 4.4, and below.

Low-band estimates (0-100EJ) are characterised by the assumption that there is very limited land (and in some cases no land) available for energy crops. This assumption is driven by scenarios in which there is a high demand for food, limited intensification of food production, and little expansion of agriculture into forested areas, grasslands and marginal land. The contribution from energy crops is correspondingly low 8-71EJ. The contribution from wastes and residues is not considered in all studies, but where included the net contribution is in the range 17-30EJ.

Estimates falling within the lower portion of the mid-band (100-300EJ) all assume that food crop yields keep pace with population growth and increased meat

Figure 4.4: Common assumptions for high, medium and low biomass potential estimates



- Crop yields outpace demand: >2.5Gha land for energy crops (includes >1.3Gha 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: >1.5Gha land for energy crops (includes >1Gha 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 demand: < 0.5Gha 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)

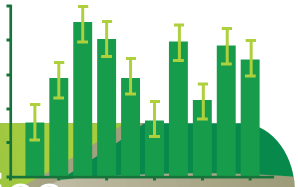
- Little or no land for energy crops (<0.4Gha total)
- High meat diet OR low input agriculture
- Limited expansion of cropland area AND high level of environmental protection
- Agricultural residues (<30EJ, not included in all studies)

[a] Agricultural residues, forestry residues, wastes (dung, MSW, industrial)

demand, but no "surplus" agricultural land is made available for energy crop production. These studies identify areas of marginal, degraded and deforested land that may be suitable for energy crops (26-174EJ, grown on 0.1-0.5Gha yielding ~10-15odt.ha^{-1} (up to a maximum ~20odt.ha^{-1} in a hypothetical irrigated scenario)). In scenarios where demand for food and materials is high, a decrease in the global forested area (up to 25%), or replacement of mature forest with young growing forest (up to 25%) may also be required. Direct extraction of biomass for energy from mature forests is only considered in one study (~10EJ). Estimates in this band include a more generous contribution from residues and wastes (60-120EJ) but this is partly because a greater number of waste and residue categories are included.

Estimates at the higher end (or spanning) the mid-band (300-600EJ) all assume that increases in food crop yields will outpace demand for food, with the result that large areas of high yielding agricultural land will be available for energy crops (>1Gha). (This feature is common to all the assessments that have used the integrated assessment model IMAGE.) In addition these estimates assume that large areas of grassland and marginal land are converted to energy crops (>0.5Gha). To give a sense of proportion it is worth noting that 1.5Gha is over 10% of the world's land mass, greater than the area of China and India combined. For most of the estimates in this band a high meat diet can only be accommodated with extensive deforestation. It is also implicit that to achieve the level of agricultural intensification and residue recovery required most animal production would have to occur in feedlots.

High band estimates (>600EJ) all describe extreme scenarios where far less land is needed for food production. This can only be achieved with combined *low-food-demand-and-high-biomass-supply* scenarios. Low food demand can be the result of either a largely vegetarian global diet and/or low global population; high biomass (food and energy) supply can either be achieved with high agricultural inputs and rapid technology-driven yield increases that outpace demand, and/or with the large scale expansion of agriculture into forested areas. The primary purpose of estimates in this band is to illustrate relationships and provide a theoretical maximum upper-bound.



5. Enduring uncertainties and controversies

The reports analysed in this review describe scenarios for the potential production of biomass for energy on a global scale. Some of these scenarios are hypothetical: they describe what *could* be done simply in order to identify the most important variables and illustrate what the implications of changing them might be (see for example Smeets et.al. (2007), and Hoogwijk et al. (2003)). Other scenarios are normative: they describe how increased biomass production *should* be implemented in order to minimise its impact on other sectors. The WBGU09 report provides an example of this second category, setting itself a goal to "show that the sustainable use of bio-energy is possible and to outline how to exploit opportunities while at the same time minimizing risks" (Schubert, et al., 2009). Yet gauging the extent to which any of these scenarios is *plausible* or *desirable* is far from straight forward. It requires taking a view across the breadth of assumptions upon which the scenarios are built, and while this is touched on in most of the reports the discussion tends to be somewhat peripheral. The objective of this chapter, therefore, is to draw together these strands, revisiting some of the key open questions, and providing additional context that might influence our interpretation of global biomass potentials.

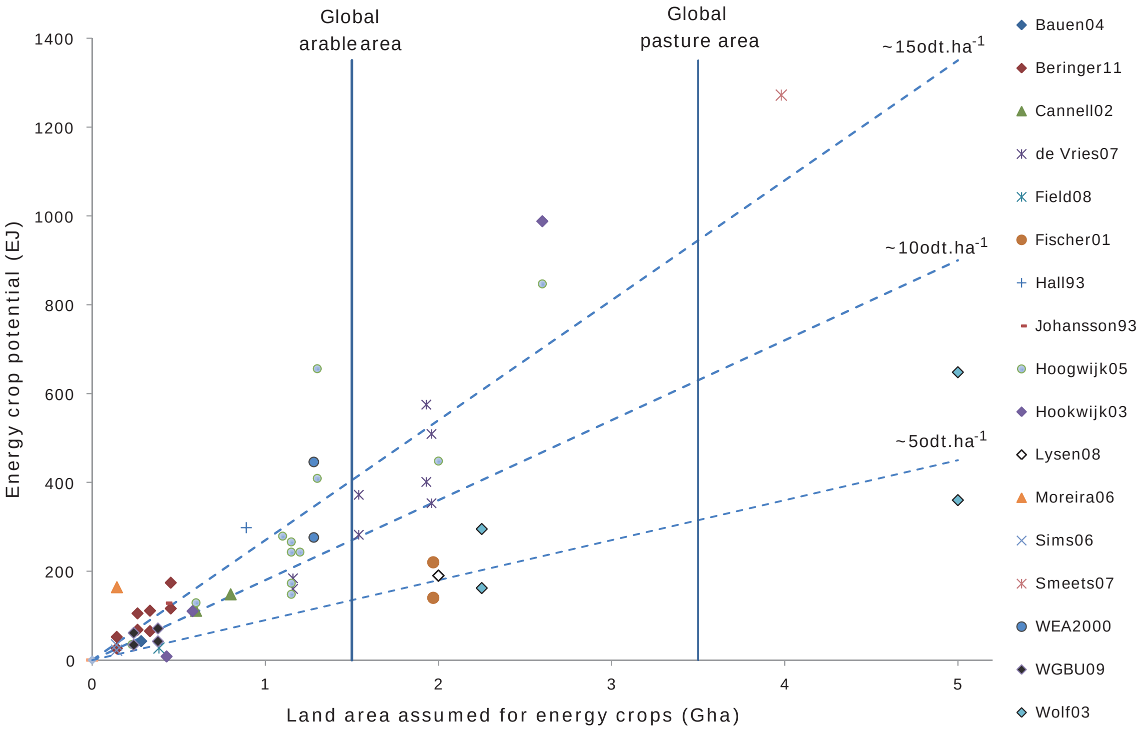
It is important to state at the outset that we cannot re-visit every assumption. Some assumptions – e.g. the future global population and diet – are demonstrably important drivers of both energy and food demand but are inherently uncertain. Of greater interest are the issues that remain contested or may be tractable to further investigation. The primary focus of this chapter is therefore on yield assumptions for food and energy crops, pre-conditions for deploying biomass at scale, and the availability of water.

5.1 Energy crops and food: land availability and yield assumptions revisited

The amount of land allocated to energy crops and the yield obtained is one of the most important factors affecting bio-energy potential estimates. The range of assumptions contained in the studies is summarised in Figure 5.1. 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 in energy crop yields. Those data points describing land areas in excess of 1Gha (and yields >5odt.ha^{-1}) assume that food crop yield growth will outpace demand.

When estimating the amount of land required for food production, the vast majority of studies – including all those using the integrated model IMAGE – follow the global yield projections outlined in a 2003 report by the FAO: World agriculture towards 2015/2030 – an FAO perspective (FAO, 2003) (and subsequent update (FAO, 2006)). The projections in this report describe yield growth for the major food crops continuing more or less linearly to 2050 – albeit at a lower level than in the past. Concerns have been raised, however, that these projections may be over optimistic and give the impression that there is greater scope for productivity

Figure 5.1: Land allocated to energy crops and assumed energy yield



increases than is actually the case. Erb et al (2009), for instance, identify that biologists tend to be sceptical. A more detailed examination of this report is therefore warranted (see Box 5.1).

The FAO's analysis was undertaken before the 2007/8 commodity price spikes and one of the background assumptions was that oil prices would decrease over the long term. Post 2007/8, concern about rapidly rising prices rekindled interest in food security and a number of detailed and high quality reviews were undertaken that examined the potential to increase food yields and meet the demands of a growing population (see for example Fischer et al. (2009), Foresight (2011), Godfray et al. (2010), Jaggard et al. (2010), Royal Society (2009), IAASTD (2009)). The broad consensus of these reviews was that it is likely to be technically possible to produce sufficient food to feed the 2050 global population, but that there will be no room for complacency – particularly if the environmental impacts of global agriculture are also to be mitigated.

Yet, it rapidly becomes apparent when examining these studies that there are inherent difficulties in undertaking a discussion about the world's capacity to produce sufficient food in abstract terms. Global agriculture is such a large and complex human endeavour that oversimplification risks giving rise to misleading generalisations. Indeed, it is reasonable to question whether the emphasis on increasing production makes sense. Smil (2005), for example, argues that focusing solely on the scope to increase food production risks forming a judgement on the basis of a badly truncated view of the world food system. A view, he asserts, that ignores issues such as post harvest losses, food wastage and many of the structural irrationalities that also exist[46]. Despite these caveats, however, Smil, like others, concludes that increasing crop productivity will be at least part of the solution, and perhaps more importantly, it will be the only way to meet the food needs in many land constrained regions such as South East Asia.

These review studies tell us that significant improvements in global agriculture are required to feed a growing population, and highlight where existing food production is unsustainable, but they do not necessarily preclude producing energy crops alongside food and feed. Rather, they provide additional emphasis to one of the key messages from the biomass potential literature: that avoiding conflicts between energy and food production will require a greater effort to improve the sustainability of conventional agriculture and the development of integrated food crop, livestock and energy crop systems.

The remainder of this section focuses on the scope to improve cereal and energy crop yields. The intention is to not to provide a comprehensive appraisal, but rather to illustrate some of the uncertainties that exist and areas of enduring contention.

5.1.1 Is it reasonable to expect cereal crop yields to continue increasing?

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 (Cassman, 1999). Since 1960, the introduction of intensified cropping systems for these species has resulted in grain production outpacing population growth without bringing additional large areas into cultivation, (Royal Society, 2009)[47]. Three production factors were largely responsible, increasing both *yield-per-unit-land and yield-per-unit-time*:

- New more vigorous hybrid varieties. These had a greater proportion of grain to biomass (higher harvest index); were shorter and therefore less prone to falling over; and matured earlier, reducing harvest losses and enabling multiple crops per year in some regions.
- Increased application of nitrogen fertilizer.
- "Massive" investments in irrigation (Cassman, 1999).

The increases achieved were spectacular: grain production more than doubled (since 1960) while, the amount of land devoted to arable agriculture globally increased by only ~9% (Godfray, et al., 2010). Looking to the future, however, it is generally

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[46] Smil (2005) gives examples of what he considers irrationalities in global food production. These include the subsidised degradation and depletion of natural resources in western countries in order to produce food surpluses which contribute to increased prevalence of obesity, heart disease and diabetes. Whereas in many developing countries neglect of agriculture, war, poverty, and institutional failure mean that there is insufficient food to feed the existing population.

[47] Despite an increase in the global population from ~3 billion in 1960 to ~6.7 billion in 2009, per capita agricultural production has still outpaced population growth. For each person alive today, there is in theory an additional 29% more food compared with 1960. It is worth noting, however, that this situation of apparent abundance co-existed with hundreds of millions of people going hungry (Royal Society, 2009) (FAO, 2003).

considered that these increases cannot be repeated (FAO, 2003, Godfray, et al., 2010, Cassman, 1999). It is also clear that they were achieved at substantial cost in terms of damage to the environment. For instance, agricultural releases of nitrogen and mobilisation of phosphorus are now of the same order of magnitude as the natural global bio-geological cycles for these elements, the negative impacts of which include eutrophication, air pollution and biodiversity loss (Vitousek, et al., 1997, Johnson, et al., 2005). Increased intensification is also one of the major risk factors associated with land degradation, unless combined with measures to conserve soil productivity. This is one area where combining food and biomass crops in crop rotations could have a beneficial effect on overall sustainability (Kort, et al., 1998, Tilman, et al., 2009, McLaughlin, et al., 1998).

The benefits of what became known as “green revolution” technologies were also not universally felt. Large parts of Africa were bypassed – a fact that has been attributed to organisational and institutional weaknesses rather than geographically limited capacity (Lynd, et al., 2011b). There may consequently be scope to increase production in these regions by extending the use of established technologies as well as new advances.

Box 5.1: Can cereal production keep pace with demand? The FAO’s 2003 perspective

The FAO’s 2003 report: World agriculture: towards 2015/2030 (and subsequent update in 2006) aimed to describe the future as it is *likely* to be, not as it *ought* to be. It predicted that an additional 1bn tonnes of cereals will be needed by 2050 to keep pace with the growing population (an increase of ~55% over 1997/1999), and envisaged that this increase in demand will be met with three sources of production growth:

The expansion of agriculture (and in particular arable crops) onto new land (20%).

- The amount of new land potentially available for arable crops was judged to be equal or greater than the existing area (1.1-1.5Gha). But it was acknowledged that the land balance models used to estimate this figure were prone to overestimation (see §3.4.2); that the global distribution was very uneven – with over 90% of available land in South America and sub-Saharan Africa; and that much of the land was subject to constraints: ecological fragility, soil toxicity, disease, and poor infrastructure. Consequently, the estimate for land expansion was limited to ~120Mha, all located in developing countries.

Increased cropping intensity (i.e. multiple harvests per year on the same area of land) (13%)

- Cropping intensity was assumed to increase as a result of shorter fallow periods and more multiple cropping. This would be made possible by increased irrigation and fertilisation. Cropping intensity, however, was acknowledged as one of the principal risk factors for land degradation.

Yield growth (i.e. more useable food per harvest) (67%)

- The scope to improve yield growth was attributed to the potential for continued incremental improvements in yields (and in particular exploitable yield gaps between the best and worst performing countries). These yield gaps would be closed through increased fertilisation, mechanisation, and irrigation and the greatest benefit would occur in countries that had not already adopted green revolution technologies. Future global growth rates were predicted to be in the range 0.9%pa over the period 1999-2050, continuing a trend of long term declining yield growth. (20yr average yield growth declined from ~3%pa in 1982 to ~1% in 2005).

Arguing from an economic perspective, the FAO's report asserted that the long term decline in cereal prices provided evidence that it was getting easier for the world to produce an additional unit of cereals, and that as productivity increased the importance of land diminished (as one factor of production along with capital and labour). A further assertion was that because large yield gaps exist between what farmers actually produce and what is attainable, farmers would respond rapidly if scarcity were to develop. Yet, the limits of this economic perspective were also acknowledged. Firstly, it pre-supposes that there are no market failures and that the resulting distribution of access to food is ethically acceptable. Secondly, it may be possible for market signals to fail to account for the environmental costs and future risks of continued intensive production. Lastly, the potential for yield growth may not exist in those countries where it will most be needed (e.g. India), exacerbating the miss-match between food producers and would-be consumers.

The report also makes it clear that following this trajectory implies extending the adoption of high input (water and fertilizer), high technology agronomy and that this is likely to exacerbate existing environmental problems. It is apparent, therefore, that the FAO's 2003 vision of how the future is *most likely* to unfold carries significant risks and environmental penalties (FAO, 2006, 2003).

The potential to increase crop yields further is most often discussed in terms of yield gaps[48]. Many alternative gaps are identified in the literature, but one of the most important is the gap between what farmers achieve (farm yield (FY)), and what could be achieved (attainable yield (AY)) using the best adapted variety, grown with optimum nutrition, water, and suffering no ill effects from disease or parasites. A second gap is the difference between the attainable yield and what might eventually be possible within the limits of crop physiology and photosynthetic efficiency (theoretical yield (TY))[49], illustrated in Figure 5.2.

Yield gaps are sensitive to location. For example, the attainable wheat yield in Finland (~3.2t.ha-1) is less than half that of the UK (~8t.ha-1), not because Finnish farmers are incompetent or under resourced, but because the growing season is shorter and wheat is less well adapted to the Finnish climate. Gaps may also change over time as yields increase with improved crops and agronomy, or decrease as pests and diseases develop

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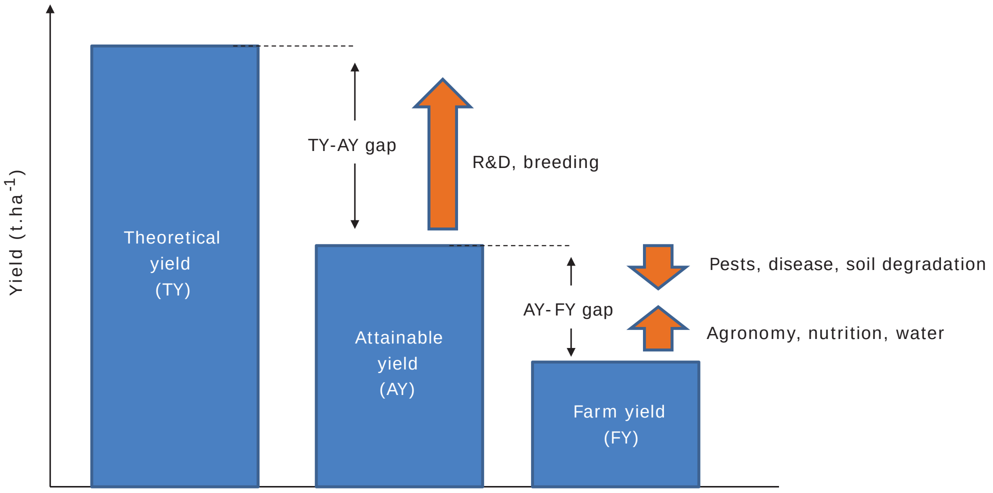
[48] Numerous other yield gaps are identified in the literature for instance *water limited attainable yield* and *economically attainable yield*, this section provides a simplified summary only.

[49] Farm yields can be measured directly. In contrast, estimating attainable yield requires highly controlled field trials or calibrated crop models. Theoretical yields can only be calculated and are far more speculative.

Figure 5.2: Yield gaps



resistance to chemical and biological controls.

The FAO has used the Agro-Ecological-Zone model (see §3.3) to estimate the AY-FY yield gap for various countries, and concludes that there is scope for yields to be improved, on the basis that large gaps exist. The USA, Ukraine, Australia and Canada for example have wheat farm yields in the range 2-3t.ha^{-1} compared to an estimated attainable yield of ~4-6t.ha^{-1}. This contrasts to the UK, France and Denmark which all have farm yields that exceed the attainable yield calculated by this method (FAO, 2003, p301). Yet, there are also good reasons to be cautious when extrapolating from the existence of a yield gap to the potential to increases farm yields. For instance Jaggard et al. (2010), argue that the AEZ methodology is too crude and the resolution too low to provide a yield gap analysis that is anything more than indicative. Whereas Sylvester-Bradley et al. (2005) contrast experience in Western Europe with experience in the US and Canada and conclude that overcoming light limitations in Europe has proved easier than overcoming water limitations in America. Experience in one region may not, therefore, provide an adequate indication of what might be possible elsewhere.

The ability to increase attainable yields and narrow the gap with farm yields depends on sources of yield improvement outpacing sources of decline. Potential sources of farm yield increases include:

- Improved crop protection (herbicides, pesticides, pathogen resistant GM crops).
- Access to fertilizer and irrigation.
- Improved agronomy (mechanisation).
- Reduced post harvest losses.
- Knowledge transfer and education.

The scope to raise farm yields will be further extended if attainable yields can be increased[50]. Sources of attainable yield gain include:

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[50] If a new variety is to have a higher yield it must intercept more solar radiation, convert more of that radiation into biomass (increased photosynthetic efficiency), or partition a greater proportion of the biomass into the desired product (Legg, 2005). In the case of wheat, large improvements have been made to maximise light capture – e.g. by optimising leaf area and orientation, and extending the growing season (delayed senescence). Similarly improvements have been made in optimising the partitioning of biomass between grain and the rest of the plant (improved harvest index). Thus far, however, no significant improvements have been made in improving the fundamental photosynthetic efficiency.

- Improved light interception, light use efficiency and harvest index – achieved through breeding and ultimately dependent on the genetic potential of the species.
- Improved resistance to minor stresses (e.g. cold nights, crowding) – achieved through breeding and better adaptation to local conditions.
- CO_2 fertilisation as atmospheric concentrations increase (this may also increase water use efficiency).

Increases in yields must also offset sources of yield decline. These include:

- Ozone toxicity[51].
- Soil degradation.
- Limits to water supply.
- Pests and diseases acquiring resistance to chemical and biological controls.
- Climate change[52] (Jaggard, et al., 2010)

The likelihood of closing yield gaps must also be considered at a practical level. Johnston et al. (2009) argue that this often depends on myriad issues not directly related to agriculture including political, economic and cultural factors. They state that major efforts have been made to close yield gaps in developing countries, only to be impeded by the lack of well-functioning transport infrastructure, distribution of inputs, and access to capital and markets.

Step changes in attainable yields require dramatic improvements in the genetic makeup of the plant. In the case of wheat, Sylvester-Bradley et al. (2005) assessed the remaining genetic potential for yield gains by examining the gap between current attainable yields in the UK (~8t.ha^{-1}) and theoretical maximum yields (~19t.ha^{-1}). They concluded that an increase of 50% on current yields (i.e. up to a maximum of 12t.ha^{-1}) was plausible[53]. It is worth noting however, that changes to the AY-TY gap are inherently more speculative that changes to the FY-AY gap. It also needs to be borne in mind that increasing yields impacts other aspects of crop agronomy and in particular water and nitrogen use. Yield and water use are closely correlated, thus high yielding varieties will use proportionately more water (Sinclair, et al., 2004). High yielding crops will also require more nitrogen, and it is possible that under conditions of nitrogen stress a variety with a high attainable yield would result in a lower farm yield compared to a better adapted lower yielding variety (ibid). Maximising production on any given piece of land is thus highly site specific (Godfray, et al., 2010).

Differences of opinion exist about the role different technologies are likely to play in increasing yields. Arguably the most controversial technology option is the use (and potential) of genetic modification[54]. Thus far, the focus of effort to grow

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[51] A meta-analysis by Feng & Kobayashi (2009) found that probable yield reductions by 2050 due to increasing ozone concentrations were 9 and 17.5 per cent for wheat and rice respectively (Jaggard, et al., 2010).

[52] Lobell et al. (2011) estimate that between 1980 to 2008 global maize and wheat production declined by 3.8 and 5.5%, respectively, relative to a counterfactual without climate trends. For soybeans and rice, winners and losers largely balanced out.

[53] The world record wheat yield is 15.6t.ha^{-1} and was set in New Zealand in 2010 (Jaggard, et al., 2010).

[54] The report by IAASTD (2009), argues that the limited and somewhat anecdotal nature of the evidence base means that it is easy for proponents and critics of GM technology to hold opposing and entrenched positions. A pragmatic view of GM technology is that it is a necessary tool in the armoury but only one part of the arsenal.

genetically modified (GM) crops has focussed on introducing genes for pest and herbicide resistance – the most notable commercial examples of which are herbicide tolerant soy beans and insect resistant maize. The introduction of these traits saves farmers time and money compared to the application herbicides and insecticides previously used, but does not improve the attainable yield; moreover, the impact on farm yields is also somewhat uncertain, as are the longer term impacts. In the case of soybeans, herbicide resistance came at the cost of slightly reduced yields (at least initially). Whereas in the case of insect (corn borer) resistant maize there is some evidence that farm yields were increased where infestations were severe, but there was no benefit when infestations were low (Gurian-Sherman, 2009). Advocates argue that rapid technological advances in genetic modification will see the introduction of desirable traits such as drought and salinity tolerance and increased nitrogen-use efficiency on a 10-15yr timescale (Godfray, et al., 2010). Those who are more prosaic argue that increased effort dedicated to genetic engineering for pest and pathogen resistance risks diverting resources from conventional breeding research – which has a more certain (albeit much longer) track record of delivering increases in both attainable and farm yields (Jaggard, et al., 2010, Gurian-Sherman, 2009, Sinclair, et al., 2004).

5.1.2 What is the potential to increase perennial energy crop yields?

As long as the area dedicated to energy crops remains smaller than the area dedicated to food production, increasing food crop yields will have a proportionately greater impact on the total energy production potential than increases in energy crop yields[55]. Nevertheless, increasing bio-energy crop yields is an important avenue of research. Much of the preceding discussion about cereal yields holds true for energy crops, but in the case of energy crops, where the whole plant will be used, there are some important differences:

- Because we are interested in total biomass production, rather than just one part of the plant (i.e. the grain), changing the harvest index will not increase the total biomass yield. Improvements will have to come from maximising radiation interception and light use efficiency. There is reason to be optimistic, however, because comparatively little effort has been devoted to perennial energy crops and there is considerable genetic diversity in the species of interest[56].
- The use of perennial grasses such as miscanthus has the potential to increase nitrogen use efficiency because much of the nitrogen contained in the plant is returned and

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[55] By way of illustrating this relationship consider a 100ha field, 90ha of which is dedicated to wheat and 10ha of which is dedicated to an energy crop. A 1% increase in wheat yields could release sufficient land to increase the amount of the energy crop produced by ~9%. Conversely a 1% increase in the energy crop yield would increase the amount of energy produced by only 1%.

[56] One of the barriers to increasing energy crop yields is that there is perceived to be little economic incentive. The market is small and royalty payments will be less than with an annual crop (Turley, 2011, pers.com.).

stored in the roots (rhizome) before it is harvested.

- Because perennial crops such as willow take several years to mature, breeding for increased yield may take longer than for annual crops unless genetic markers for desirable traits can be found (Karp, et al., 2008).

The majority of global biomass potential studies model energy crops at a highly aggregate level, either assuming a representative yield without specifying a species, or estimating regional NPP and assuming that a proportion of this could be captured. The most detailed approach used is the LPJmL crop model. This includes 13 food crop types and 3 energy crops, each is represented as a functional type (see Schubert et al. (2009), Beringer et al. (2011). But as already noted (see §3.3) in the absence of empirical evidence obtained over many years and from many locations, all these methods are inherently speculative.

5.1.3 Insights

This discussion only scrapes the surface of a literature far more extensive than the one we have examined thus far on global biomass potentials. There are many other aspects of agricultural production that could be drawn into the debate. For instance, improving animal nutrition and feed conversion could increase the efficiency of meat and milk production, thereby reducing pressure on land, as could obtaining animal food from novel sources (e.g. hydrolysed crop residues) (Wirsenius, et al., 2010, Sparovek, et al., 2007). If it is conjectured that dietary changes are feasible, then a shift from eating beef and lamb to pork and chicken could reduce the need for extensive pasture, as could eating less meat more generally (Wirsenius, et al., 2010, Godfray, et al., 2010)[57]. There may also be potential to increase the use of underexploited crops that have received far less attention than the major cereals, for instance cassava and quinoa (Jaggard, et al., 2010). A further consideration is the use of techniques such as reduced tillage, or integrated pest management (these are examples of a broad range of technologies that have been termed "sustainable intensification" (Royal Society, 2009). In some cases there may be a choice between reducing yields in the short term in order to maintain yields in the longer term.

Yet, despite its limited scope, this discussion illustrates the complexities involved in forming a view of future agricultural production. It also provides some broad insights that might reasonably influence our interpretation of the bio-energy literature. These include that:

- The green revolution led to production outpacing demand but at a major cost to the environment, and with greatly increased energy and water inputs.
- Scope to further increase yields and close yield gaps exists but there is a general sense that many of the easy gains have already been achieved. The practicality of closing yield gaps is also hotly contested.

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[57] In terms of the dry weight of feed intake per fresh weight of product, beef (~50kg/kg) and mutton (~53kg/kg) require roughly ten times as much feed as pork (~4.3kg/kg) or poultry (~3.3kg/kg). Global average animal productivity in the period 1961-2005 increased at ~1-1.5% pa, as a result of breeding, and improved nutrition (Wirsenius, et al., 2010) .

- Intensification of agricultural production 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.
- Increasing food crop yields may provide a faster way to increase biomass production than increasing energy crop yields.

But perhaps the most important insight is that prognostications about the future of food production are themselves highly abstract and involve a fair degree of speculation. The corollary to this is that where energy crop models have used aggregate productivity projections from the FAO they must necessarily be considered as highly theoretical modelling exercises: effective at identifying the most important relationships but possessing little predictive capability. Conversely, sweeping dismissals of the prospect of integrating energy crop production into existing agricultural systems must also be viewed with caution.

5.2 What pre-conditions are there for sustainable energy crop potentials to be implemented?

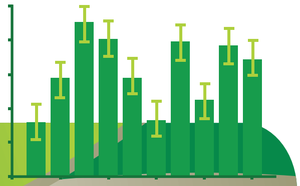
The sustainable energy crop potentials described in the normative scenarios only exist in the sense that their authors consider them to be feasible visions of the future. To form a view on their practicality and likelihood, it is useful to consider what the pre-conditions for implementation might be. The most in depth discussion on this subject is provided in the WBGU09 report (Schubert, et al., 2009). This report describes three factors considered to be of particular importance:

- A minimum of investment activity. This in turn cannot take place without a minimum level of security and stability, without which there is no suitable foundation for the creation of a dynamic bio-energy farming system.
- The development of infrastructure and logistics capacities – which in many developing countries do not yet exist
- A minimum level of regulatory competence. To pursue a sustainable trajectory it is necessary to define the legal framework, and to monitor and enforce adherence to it.

Given that ~20% of the global population is employed in agriculture, the need for knowledge transfer, and education could also be added to this list.

The extent to which these factors can be met is unknown, but perhaps the best indication would 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, and stimulate rural development might all reasonably be examined.

It is also interesting to consider whether these factors might apply equally to the future development of sustainable agriculture. Comparable to visions of the future in which bio-energy plays a significant role, the sustainable intensification of conventional agriculture cannot necessarily be presumed to occur of its own accord, even if it is ultimately in our long term interest. It is also possible



that controls put in place to prevent the unsustainable development of bio-energy could be applied more broadly to agricultural development. In this context it is worth reiterating the FAO's caveat to its own analysis: *"it may be possible for market signals to fail to account for the environmental costs and future risks of continued intensive production"* (FAO, 2003). Taken at face value, this statement could be used as a basis to argue for increased or decreased government intervention in agriculture, depending on whether intervention is viewed as a cause or remedy of market failure.

5.2.1 Economic bio-energy potentials

This review does not consider the economics of biomass production in any depth, reflecting the fact that it is given only cursory treatment in the evidence base. Yet economic viability is clearly an important pre-condition for deployment. The principal study that examines this issue is deVries07, which reiterates work presented in Hoogwijk04. Hoogwijk's (2004) analysis is intrinsically hypothetical and is primarily of interest because it is the first attempt to estimate long-term regional and global supply curves for biomass[58]. Owing to its hypothetical nature, the insights that the study provides are somewhat limited. The main points of interest to this discussion are:

- That the economic biomass potential is highly sensitive to the productivity of the land. Production on good quality land will be cheaper than on poor quality land if land costs are excluded.
- That increased mechanisation will tend to reduce costs.

Hoogwijk (2004) also excludes the possibility of economic production on "low productivity" land because the yield is too low (<3t.ha^{-1}) for this to be viable.

Other studies that consider the economic potential simply apply economic availability factors. Fischer et al. (2001a), for instance, opine that 50% of their technical energy crop potential estimate is a reasonable guide of the economic potential, but no rationale for choosing this figure is provided.

Although brief, this consideration of economic potentials provides two insights pertinent to the broader discussion:

- The global economic biomass potential will by definition be less that the theoretical or technical potential, but how much less is unknown, and for practical decision making purposes may be unknowable.
- Biomass developers will have a strong incentive to identify productive, low cost land. There is a very possible scenario, as identified by Rokityanskiy et al. (2007), where the option that stimulates greatest uptake of bio-energy, is not the same solution that gives best environmental protection globally or locally.

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[58] Future costs are based on extrapolating the capital and labour cost estimates for the Netherlands, Ireland and Nicaragua, reduced by expectations of future cost reductions through technological learning. Land rental values are estimated as the difference between the market value for cereals and the assumed production costs (which in turn depend on the land quality).

5.2.2 Land acquisition for energy crops

The remote sensing approaches that underpin land availability estimates are not able to identify who owns an area of land or who might be using it. Property rights, when assessed at a local level, can be highly complex and there may be major social risks in undertaking large scale projects (Ariza-Montobbio, et al., 2010, Beringer, et al., 2011). The time taken to arrange access to land on an equitable basis may also be the rate limiting step for expanding energy crop production. This is an area where lessons of past successes and failures in conventional agriculture might provide a useful comparison.

This issue of land access and ownership is particularly acute when it comes to the potential use of marginal and degraded land (see Box 5.2). Grazing lands which are productive during the rainy season but look barren during the dry season are often classified as degraded (Ariza-Montobbio, et al., 2010). These areas are often not privately owned, but are frequently used extensively by the rural poor (Schubert, et al., 2009). From an agronomy perspective, the growing conditions also tend to be difficult with low yields and high production costs (Wicke, et al., 2011a, 2011b).

5.3 The importance of water for biomass production

Globally, agriculture accounts for ~70% of all fresh water use, and scarcity is a growing concern (UN, 2007). The vast majority of this water is consumed during crop cultivation: either evaporated from the soil or transpired from the leaves of plants (evapo-transpiration) (UN, 2007, Berndes, 2002).

Yield and water transpiration are closely correlated and maximum crop growth only takes place when water availability is not restricted (Legg, 2005). Crop growth

Box 5.2: The promotion of jatropha in Southern India – a cautionary tale

Jatropha is a hardy shrub promoted as potential source of biofuels on the basis of its claimed drought tolerance, suitability for marginal land reclamation and potential to support rural development. Assessing the performance of jatropha plantations in Tamil Nadu, India, Ariza-Motobbio et al. (2010) found that these claims were "too good to be true". Large inputs of water and fertilizer were required in order for the crop to be productive and yields were ~1/10th of those anticipated from research station trials. This rendered the crop economically unviable. The contribution to rural development was also questionable. The authors describe how the "pro-poor" rhetoric was used to build legitimacy for contract farming that only favoured resource rich farmers and further jeopardising the livelihoods of the poorest. Moreover, because there was no clear definition of the marginal lands to be developed, policies to prevent competition with agricultural land use were ineffective or subverted. Ultimately, the crop proved to be a poor fit with the ecological and socio-economic condition and ~70% of plantations were uprooted or abandoned.

models[59] are able to predict water restricted yields for both food and energy crops, but competing demands on water supplies are not considered in depth. Irrigated energy crop scenarios are investigated in the WBGU09 and Beringer11 studies, but the authors of these reports consider them unlikely to be sustainable. The majority of other studies assume that energy crop production will be rain-fed. Assuming rain-fed production is not without problems, however, as modelled changes in conventional agriculture, and in particular, productivity growth and intensification also imply increased irrigation and water use (IPCC, 2011).

Water use efficiency (WUE) is the ratio of dry aboveground biomass to the amount of water evaporated and transpired. WUE varies with crop type, for instance the tropical (C4) grasses – maize, miscanthus, sugar cane – use less water than temperate (C3) crops such as wheat (although they don't grow well at low temperatures) (Berndes, 2008). Agronomy can also have an important influence: planting and harvesting operations can be timed to extend canopy closure and maintain ground cover, thereby increasing WUE in regions where soil evaporation is high (Sylvester-Bradley, et al., 2005). Integrating perennial and annual crop production may also help increase productive crop transpiration and can also improve water infiltrating into the soil. Depending on the location and the character of the land (including current and previous uses) the hydrological consequences can vary on landscape level. Groundwater replenishment may increase or decrease and run-off rates can also change – either to the benefit or detriment of those downstream (IPCC, 2011).

In contrast to these management options, the potential for breeding individual crops to increase WUE is less certain. Focussing on wheat, Sylvester-Bradley et al. (2005) argue that other than changes in the harvest index there is little evidence that WUE has improved as yields have increased. Increasing drought tolerance – by for instance reducing transpiration from leaves – would also come at the expense of increased yield because it restricts the level of CO_2 in the leaf which reduces the rate of photosynthesis (ibid).

More generally, there is an important distinction between surviving and thriving. If an annual crop survives drought but produces a negligible yield then its survival may be of little benefit (Sinclair, et al., 2004). For perennial crops, survival in times of drought may provide a considerable advantage.

The IPCC concludes that 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. Opportunities for improvement in water use appear to exist but need to be proven, and, as with many other aspects of biomass production, effective management will be essential (IPCC, 2011, Berndes, 2002).

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[59] See for instance the studies that use the IMAGE or LPJmL crop models: Table 3.4.

5.4 Other considerations

5.4.1 The relationship between intensification and land sparing

An important assumption in many of the biomass potential models is that if agricultural yields increase, crop and pasture land will be spared from production and may be available for energy crop production or nature conservation.

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, providing the farmer with an incentive to increase the cultivated area (and their gross income) (Rudel, et al., 2009). Empirical studies undertaken at local and regional levels provide evidence of both land consuming and land sparing effects from intensification. Examining the effect at a global level is difficult, however, as robust data on abandoned land does not exist (ibid).

Criticisms of the land sparing hypothesis include that:

- There is a rebound effect, whereby increasing yields of staple crops frees up labour thus permitting larger areas of other crops to be grown.
- Government subsidies may override classical economic constraints.
- Land spared from agriculture may be used for other purposes (Ewers, et al., 2009).

Examining changes in cultivated arable areas between 1970 and 2005, Rudel et al. (2009) found that "only between 1980-85 in the aftermath of a sustained decline in agricultural commodity prices and a steep rise in yields during the 1970's does agricultural intensification appear to induce declines in cultivated areas". Examining the circumstance of individual countries in which land sparing occurred, they concluded that increasing yields cannot be assumed to increase cropland abandonment without explicit political intervention. In a similar study looking at the period 1979-99, Ewers et al. (2009) found some evidence that developing countries that had increased staple crop yields most rapidly had a slower deforestation rate than might otherwise have been the case. These authors concluded that land sparing was a weak process that can have positive outcomes for nature conservation but only happen in a limited set of circumstance.

5.4.2 Potential for new sources of biomass

It is possible that in the period up to 2050 additional sources of biomass may be identified or developed. One such possible resource is algal biomass. Macro-algae (seaweed) may be harvested from the shorelines or cultivated on long ropes and can be digested to produce biogas. Micro-algae may be cultivated in raceway ponds or photo-bioreactors to produce lipids and starch which may be used to produce biodiesel or ethanol. Major advances, however, would be required to make these technologies viable for energy production and it is reasonable to exclude algal biomass from global potential estimates at the present time (Lundquist, et al., 2010, Bruton, et al., 2009, Aquafuels, 2011).

5.4.3 IPCC's 2011 perspective on biomass

The Intergovernmental panel on climate change (IPCC) released a special report on renewable energy sources and climate change mitigation in 2011. This report includes a detailed chapter on biomass resource potentials that draws on many of the papers discussed here. The IPCC authors conclude that the technical potential of biomass depends on "factors that are inherently uncertain"[60] and cannot be determined precisely while societal preferences are unclear. With these caveats in mind, the authors suggest that by 2050 biomass deployment of could reach 100-300EJ, but could evolve in a sustainable or unsustainable way. To pursue a sustainable trajectory, they state that it is necessary for land use to be managed and governed effectively, for agricultural and forestry yields to be increased and competing demands for food and fibre to be moderate (IPCC, 2011).

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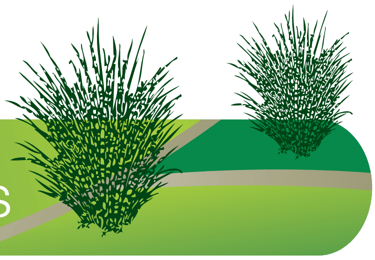
[60] The IPCC identifies factors of particular importance including: population and economic/technological developments, the way in which these translate into demand for fibre, fodder, food and water, and changes to agricultural and forestry production systems.



6. Conclusions and recommendations

6.1 Context

This report aims to support an informed debate about the extent to which biomass could contribute to future global energy supply by addressing the following question:

> *What evidence is there that using biomass to supply modern energy services can make a major contribution to future global energy supply, without unacceptable consequences?*

We use a systematic review methodology to identify estimates of the global biomass resource that have been published over the last 20 years, focussing on the academic literature and other reputable sources such as reports by governments and international organisations. These estimates are analysed to expose the assumptions that lie behind them and their influence on biomass potential estimates. The insights this literature provides into the interactions between biomass production, conventional agriculture, land use, and forestry are also examined.

Replacing the entirety of fossil fuel supply with biomass would be an endeavour comparable in size to all of existing global agriculture and commercial forestry combined. None of the evidence examined for this report suggests that this is a practical or desirable proposition. Yet biomass already contributes around 10% to global energy supply, the major part of which takes the form of traditional uses such as firewood gathering. Given that global energy demand is expected to increase rapidly, the potential for an increased contribution from biomass is of considerable importance; a fact reflected in the prominent role biomass is given in energy scenarios developed by the International Energy Agency, amongst others.

Ultimately, societal preferences for food, energy and environmental protection will determine the extent to which biomass is used to provide energy services, and whether production happens in a sustainable or unsustainable way. This report does not, therefore, seek to prescribe what an *acceptable* level of biomass production might be. It simply aims to expose how different levels of deployment necessitate assumptions that could have far reaching consequences for global agriculture, forestry and land use, ranging from a negligible impact to a radical reconfiguration of current practice.

Biomass for energy may be obtained from a diverse range of sources, the most important of which are *energy crops, agricultural and forestry residues, wastes*, and *existing forestry*[61]. By far the largest range of potentials relate to *energy crops* (from nil up to the entirety of current global primary energy supply). Because these crops require land and water, they also stimulate the most discussion about whether deployment at scale could be beneficial – mitigating some of the environmental damage caused by conventional agriculture; or detrimental – increasing competition for land and thus contributing to food price increases. In agreement with previous studies, this review finds that land availability is the most important factor influencing the

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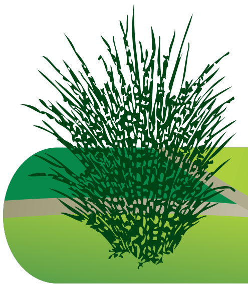
[61] This category of biomass describes the fraction of global annual forest growth that is deemed accessible and available. It includes mature forestry although some studies exclude bio-diverse areas such as the Amazon.



contribution that *energy crops* might be able to make. This is primarily determined by:

- Per capita food consumption and diet.
- Global population.
- The ability to maintain and increase food production on the existing agricultural area.
- The availability of water.
- Areas set aside for nature conservation.

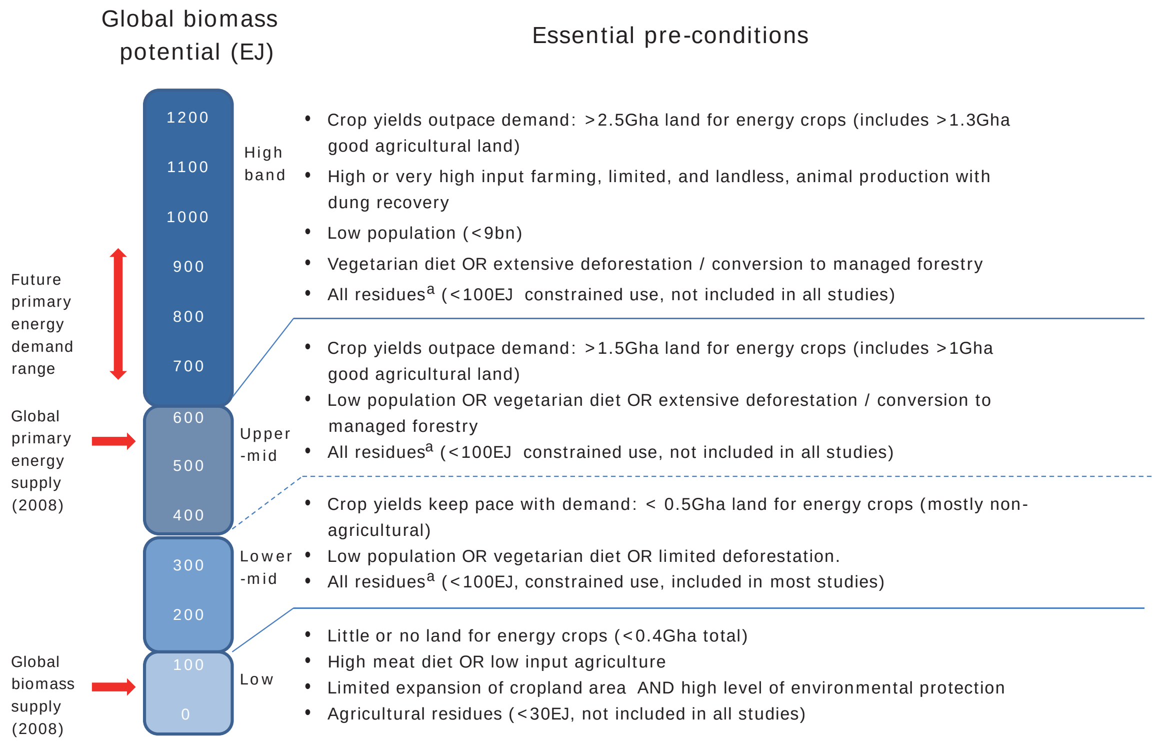
The other categories of biomass – *agricultural and forestry residues, wastes* and *existing forestry* – are comparatively neglected in global studies but could potentially make a contribution comparable in size to the existing use of biomass for energy. Practical and environmental constraints may limit the use of agricultural and forestry residues. The last of these categories, *existing forestry*, is excluded from many studies because of perceived negative impacts on biodiversity.

6.2 Assumptions underpinning biomass potential estimates

The assumptions contained in global biomass potential studies were analysed in terms of four bands describing increasing levels of biomass deployment. These bands are described in Figure 6.1 and elaborated below.

- Estimates up to ~100EJ (~1/5th of current global primary energy supply) are characterised by the assumption that there is very limited land (and in some cases no land) available for energy crops. This assumption is driven by scenarios in which there is a high

Figure 6.1: Common assumptions for high, medium and low biomass potential estimates



High band:

- Crop yields outpace demand: >2.5Gha land for energy crops (includes >1.3Gha 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)

Upper-mid:

- Crop yields outpace demand: >1.5Gha land for energy crops (includes >1Gha 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)

Lower-mid:

- Crop yields keep pace with demand: < 0.5Gha 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)

Low:

- Little or no land for energy crops (<0.4Gha total)
- 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, MSW, industrial)

demand for food, limited intensification of food production, and little expansion of agriculture into forested areas, grasslands and marginal land. The contribution from energy crops is correspondingly low 8-71EJ. 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.

- Estimates falling within the range 100-300EJ (roughly half current global primary energy supply), all assume that food crop yields keep pace with population growth and increased meat consumption. Little or no agricultural land is made available for energy crop production, but these studies identify areas of marginal, degraded and deforested land ranging from twice the size of France to ten times the size of France (<0.5Gha). In scenarios where demand for food and materials is high, a decrease in the global forested area (up to 25%), or replacing mature forest with young growing forest may also be required. Estimates in this band include a more generous contribution from residues and wastes (60-120EJ) but this is partly because a greater number of waste and residue categories are included.

- Estimates in excess of 300EJ and up to 600EJ (600EJ is slightly more than current global primary energy supply) all assume that increases in food-crop yields will outpace demand for food, with the result that an area of high yielding agricultural land the size of China (>1Gha) becomes available for energy crops. In addition these estimates assume that an area of grassland and marginal land larger than India (>0.5Gha) is also converted to energy crops. Thus in these scenarios the area of land allocated to energy crops could 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 band a high meat diet could only be accommodated with extensive deforestation. It is also implicit that to achieve the level of agricultural intensification and residue recovery required, most animal production would have to occur in feedlots. A contribution from residues and wastes is not included in all studies but where included is in the 60-120EJ range.

- Estimates in excess of 600EJ describe extreme scenarios. The primary purpose of which is to illustrate the sensitivity of biomass estimates to key variables such as population and diet, and to provide a theoretical maximum upper-bound.

6.3 The merits and limitations of global biomass potential studies

Biomass potential studies do not try and describe what is likely to happen. 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 development. They are optimistic in the sense that they try to describe sustainable paths as opposed to unsustainable ones. What they are not is forecasts extrapolated from empirical observations or any practical experience of trying to

achieve these sorts of transitions at a global scale. This is not always obvious from the way in which modelling results are sometimes interpreted or described.

Although optimistic in spirit, biomass potential studies are not blind to the challenges. Pre-requisites to pursuing a sustainable trajectory are discussed in the majority of studies, and include:

- Investment in deployment, agricultural development, and forestry.
- The development of infrastructure and logistics.
- Capacity building and knowledge transfer.
- Appropriate regulation and a minimum level of regulatory competence.

Risks are also highlighted, including the fact that:

- Sustainable biomass may cost more than unsustainable biomass.
- Global population and diet which are the root drivers for food and energy demand are also inherently uncertain.

One of the criticisms levied at biomass potential assessments has been the lack of standardised and consistent methodologies. Yet the analysis presented in this report shows that the range of estimates is driven more by the choice of alternative assumptions than methodological differences. One area where harmonisation might be valuable, however, is the use of descriptive terms that are precise but not value laden. Terms such as *abandoned land* and *surplus forestry* when used to describe large areas of the planet's surface have the potential to be misinterpreted.

6.4 The interplay between biomass and food scenarios

A large scale global bio-energy sector would need to be closely integrated with conventional agriculture. Predictions of how agriculture is most likely to evolve have been developed by the FAO and are used in the construction of biomass scenarios. But there are many caveats to the FAO's analysis. Some of the most important assumptions, for example the potential for yield increases in major crops, are contested, or are in turn dependent on favourable investment and energy price scenarios. These issues compound the uncertainties inherent in energy crop models.

Yet there are also many similarities between food and biomass assessments, they draw on the same FAO data sets, and use many of the same models. The principal difference is that in the case of food production it is possible to extrapolate from existing trends to forecast what is *likely to happen*, whereas in the case of biomass it is only possible to produce scenarios that describe what *might be possible*.

The issue of environmental impacts is also given different weight in each literature. In the case of food an increased impact on the environment is framed as the likely, albeit undesirable consequence of increased demand. Whereas in the case of biomass-for-energy environmental impacts are framed as setting the boundaries for what is acceptable.

Analysing recent studies that have focused on the security of global food production

provides a number of insights that might reasonably influence our interpretation of biomass potentials. These include:

- The green revolution led to production outpacing demand but at a major cost to the environment, and with greatly increased energy and water inputs.
- Scope to further increase yields and close yield gaps exists but there is a general sense that many of the easy gains have already been achieved. The practicality of closing yield gaps is also hotly contested.
- Intensification of agricultural production 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.

Improving crop productivity has the potential to be a win-win option for energy and food provision as long as it is done without causing long term damage to soil fertility or depletion of water resources. Improving animal feed conversion and the efficiency of milk and meat production also has the potential to be part of the equation.

6.5 Using global biomass potentials to inform decisions

Prognosticating about future global food and biomass supply is not an exact science. There are uncertainties that cannot be resolved, and trade-offs that will always be contested. Policymaking needs to proceed in the light of this inherent uncertainty.

In this context, one of the most helpful interpretations of global biomass assessments may be to highlight the need for action. If biomass is believed to be a necessary component of future global energy supply, as in many energy scenarios, then more needs to be done to make it a sustainable option. This is also where global biomass assessments are most useful. They highlight the opportunities, describe the scale of the challenge and help make many of the trade-offs explicit.

Some of the trade-offs that would be required to make space for large amounts of biomass for energy go against existing global trends: for instance, the trend for increasing meat consumption as incomes rise. Others are controversial: for example the public acceptance of land use change. Many more, for example the implications of large scale energy crop production on water quality and availability, remain poorly understood.

Scenarios in which there is a technological solution, such as increasing yields, or integrating food and biomass production, may offer the least controversial way forward, but again this is an option that requires an active decision to pursue. Solutions that integrate food, forestry, and biomass for energy are also appealing, but have yet to be proven at scale. They may also challenge conventional business models.

Relating global biomass potentials to the domestic targets of any individual country requires careful consideration. It is possible to argue, for instance, that if the global potential were 200EJ and the UK remained 2% of the global economy that it might be able to access this share of the

overall potential (i.e. 4EJ). But a target based on such a rationale risks communicating a misleading level of precision while the effort involved in mobilising the global biomass resource at this level remains unknown.

6.6 Open questions and opportunities

Global biomass potential studies help elucidate what would need to happen if biomass was used to provide energy services on a global scale. These insights are not predictions, the datasets used are imperfect, and the diversity and complexity of global agriculture cannot be fully captured in any of the modelling approaches used.

Setting aside issues that are inherently uncertain, such as dietary changes, many of the important open questions highlighted by this review are tractable to further research. The claimed benefits of integrated food and biomass production, for instance, could be evaluated at scale. As could the feasibility, and sustainability benefits, of extending energy crop production onto marginal, degraded and deforested land.

The future productivity of both food and energy crops is an issue of critical importance and, here also, there are a number of aspects that merit investigation:

- Because energy is one of the primary inputs into food production there are inevitable interactions between energy and food prices and production systems. This interaction is poorly reflected in the literatures on both biomass and food. As a result, projections of global food production developed by the FAO are based on business-as-usual baselines for energy prices. While at the same time, the scenarios used to develop biomass potential estimates incorporate projections of food productivity that may not adequately reflect the range of uncertainties and risks associated with increased intensification. A greater level of integration may lead to an improved level of overall understanding.
- The argument that increasing food crop yields will free up land for energy crop production or nature conservation underpins a lot of modelling work but the causal relationship is weak and merits further investigation.
- Water use efficiency is an important constraint on producing food and energy crops. Opportunities for improvement are believed to exist, but need to be proven at scale.

Given that appropriate regulation is considered one of the pre-requisites for sustainable implementation, there is an opportunity to monitor the efficacy of regulatory approaches such as biomass sustainability certification and use this real world experience to inform decisions and projections of what might be possible in the future.

The opportunity to experiment and gather empirical evidence should also not be overlooked. Provided they are based on the sustainable use of land resources many investments in bio-energy are ultimately reversible. Focussing on tangible opportunities could help identify the merits and pitfalls of expanding

biomass deployment. At a global level concentrating on the first 100EJ, where it is and what obstacles need to be overcome to make it available, may help improve our understanding of the level of effort involved in going to higher levels of biomass use.

The debate about the contribution that biomass might make to future energy supply is likely to endure. Addressing practical issues and tackling these key questions might help lay the foundations of a sustainable bio-energy sector, however large it proves to be in the future.

References

ALEXANDRATOS, N., ED. (1995) *World agriculture: towards 2010. An FAO study*. Chichester, UK, John Wiley and Rome, FAO.

ARIZA-MONTOBBIO, P., LELE, S., KALLIS, G. and MARTINEZ-ALIER, J. (2010) The political ecology of Jatropha plantations for biodiesel in Tamil Nadu, India. *Journal of Peasant Studies*.

AQUAFUELS (2011) Aquafuels: algae towards biofuels: Life-Cycle Assessment and Environmental Assessment (Project report). [Available from <www.aquafuels.eu/deliverables.html>]

BAUEN, A., WOODS, J. and HAILES, R. (2004) *Bioelectricity Vision: achieving 15% of electricity from biomass in OECD countries by 2020*. E4tech (UK) Ltd.

BEE (2008) *Status of biomass resource assessments - version 1: a report for the Biomass Energy Europe (BEE) project - FP7 Grant Agreement 213417*. IFEU. [Available from: <www.eu-bee.com/>].

BERINGER, T., LUCHT, W. and SCHAPHOFF, S. (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy*, 3, 299-312.

BERNDES, G. (2002) Bioenergy and water: The implications of large-scale bioenergy production for water use and supply. *Global Environmental Change*, 12, 253-271.

BERNDES, G. (2008) *Water demand for global bioenergy production: trends, risks and opportunities*. WBGU, Berlin [Available from: <www.wbgu.de/wbgu_jg2008_ex02.pdf>].

BERNDES, G., HOOGWIJN, M. and VAN DEN BROEK, R. (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass & Bioenergy*, 25, 1.

BOATMAN, N., STOATE, C., GOOCH, R., CARVALHO, C., BORRHLHO, R., SNOO, G. and EDEN, P. (1999) *The environmental impact of arable crop production in the European Union: practical options for improvement - a report prepared DGXI of the EU Commission*. [Available from: <http://ec.europa.eu/environment/agriculture/pdf/arable.pdf>].

BONDEAU, A., SMITH, P., ZAEHLE, S., SCHAPHOFF, S., LUCHT, W., CRAMER, W., GERTEN, D., LOTSE-CAMPDED, H., MULLER, C., REICHSTEIN, M. and SMITH, B. (2007) Modelling the role of agriculture for the 20th century global terrestrial carbon balance. *Global Change Biology*, 13.

BP (2011) *BP Statistical Review of World Energy*. [Available from: <bp.com/statisticalreview>].

BRUTON, T., LYONS, H., LERAT, Y., STANLEY, M. and RASMUSSEN, M. B. (2009) *A review of the potential of marine algae as a source of biofuel in Ireland*. Sustainable Energy Ireland. [Available from: <http://www.seai.ie/Algaereport.pdf>].

CANNELL, M. G. R. (2003) Carbon sequestration and biomass energy offset: theoretical, potential and achievable capacities globally, in Europe and the UK. *Biomass and Bioenergy*, 24 97-116.

CASSMAN, K. G. (1999) Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *PNAS*, 96, 5952-5959.

DALE, B. E., BALS, B. D., KIM, S. and ERANKI, P. (2010) Biofuels done right: land efficient animal feeds enable large environmental and energy benefits. *Envrionmental science and technology*, 44 8385-8389.

DE VRIES, B. J. M., VAN VUUREN, D. P. and HOOGWIJK, M. M. (2007) Renewable energy sources: Their global potential for the first-half of the 21st century at a global level: An integrated approach. *Energy Policy*, 35 2590-2610.

DESSUS, B., B. DEVIN and PHARABED, F. (1992) *World potential of renewable energies: actually accessible in the nineties and environmental impact analysis*. la Huille Blanche No. 1, Paris.

E4TECH (2009) *Biomass supply curves for the UK: a report for DECC*. E4tech.

EDMONDS, J. and REILLY, J. (1983) *A long-term global energy economic model of carbon dioxide release from fossil fuel use*. Butterworth & Co.

EIDE, A. (2008) *The right to food and the impact of liquid biofuels (agrofuels)*. Food and Agriculture Organization of the United Nations, Rome. [Available from: <http://publish.uwo.ca/~dgrafton/righttofood.pdf>].

ERB, K.-H., HABERL, H., KRAUSMANN, F., LAUK, C., PLUTZAR, C., STEINBERGER, J. K., MÜLLER, C., BONDEAU, A., WAHA, K. and POLLACK, G. (2009) *Eating the planet: Feeding and fuelling the world sustainably, fairly and humanely - a scoping study (Commissioned by Compassion in World Farming and Friends of the Earth UK)*. Institute of Social Ecology and PIK Potsdam, Vienna, Potsdam.

EWERS, R., SCHARLEMANN, J., BALMFORD, A. and GREEN, R. (2009) Do increases in agricultural yield spare land for nature? *Global Change Biology*.

FAAIJ, A. P. C. (2006) Bio-energy in Europe: changing technology choices. *Energy Policy*, 34, 322.

FAO (2003) World agriculture: towards 2015/2030 - an FAO perspective. IN BRUINSMA J. (Ed.). London:Earthscan and FAO: Rome.

FAO (2006) *World agriculture: towards 2030/2050: interim report*. FAO, Rome.

FAO (2009) How to feed the world in 2050. *How to feed the word 2050: high level expert forum*. Rome (12-13 October), Food and Agriculture Organisation (FAO).

FAO (2010) *OECD-FAO Agricultural outlook 2010-2019*. FAO, Rome.

FIELD, C. B., CAMPBELL, J. E. and LOBELL, D. B. (2008) Biomass energy: the scale of the potential resource. *Trends in Ecology and Evolution, 23.*

FISCHER, G. and SCHRATTENHOLZER, L. (2001a) Global bioenergy potentials through 2050. *Biomass and Bioenergy* 20, 151–159.

FISCHER, G. and SCHRATTENHOLZER, L. (2001b) Global bioenergy potentials through 2050. *Biomass and Bioenergy*, 20, 151-159.

FISCHER, G., VELTHUIZEN, H. V. and NACHTERGAELE, F. O. (2000) *Global Agro-Ecological Zones Assessment: methodology and results (Interim report: IR-00-064)*. IIASA.

FISCHER, R. A., BYERLEE, D. and EDMEADES, G. O. (2009) Can technology deliver on the yield challenge to 2050? *FAO Expert Meeting on How to Feed the World in 2050*. Rome (24-26 June), FAO.

FORESIGHT (2011) *Foresight: the future of food and farming - final project report*. The Government Office for Science, London.

GBEP (2008) *A review of the current state of bioenergy development in G8 + 5 countries*. FAO, Rome.

GODFRAY, H. C. J., BEDDINGTON, J. R., CRUTE, I. R., HADDAD, L., LAWRENCE, D., MUIR, J. F., PRETTY, J., ROBINSON, S., THOMAS, S. M. and TOULMIN, C. (2010) Food security: the challenge of feeding 9 billion people. *Science* 327.

GOS (2011) *Foresight project on global food and farming futures synthesis report C2: changing pressures on food production systems*. Government Office for Science (GOS) [Available from: <www.bis.gov.uk/Foresight>].

GRAINGER, A. (1988) Estimating areas of degraded tropical lands requiring replenishment of forest cover. *International Tree Crops Journal*, 5, 31-61.

GURIAN-SHERMAN, D. (2009) *Failure to yield: evaluating the performance of genetically engineered crops*. UCS Publications, Cambridge, MA.

HABERL, H., BERINGER, T., BHATTACHARYA, S. C., ERB, K.-H. and HOOGWIJK, M. (2010) The global technical potential of bio-energy in 2050 considering sustainability constraints *Current Opinion in Environmental Sustainability*, 2.

HABERL, H., ERB, K. H., KRAUSMANN, F., GAUBE, V., BONDEAU, A., PLUTZAR, C., GINGRICH, S., LUCHT, W. and FISCHER-KOWALSKI, M. (2007) Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *PNAS*.

HALL, D. O. and MOSS, P. A. (1983) Biomass for energy in developing countries. *GeoJoumal*, 7.1.

HALL, D. O., ROSILLO-CALLE, F., WILLIAMS, R. H. and WOODS, J. (1993) Biomass for Energy: Supply Prospects. IN T.B. JOHANSSON ET AL (Ed.) *Renewable Energy: Sources for Fuels and Electricity*. Washington, D.C, Island Press.

HAMELINCK, C. N., FAAIJ, A. P. C., DEN UIL, H. and BOERREGHTER, H. (2004) Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential. *Energy*, 29, 1743-1771.

HAY, R. K. M. (1995) Harvest index: a review of its use in plant breeding and crop physiology. *Annals of Applied Biology*, 126, 197.

HAY, R. K. M. and WALKER, A. J. (1989) *An introduction to the physiology of crop yield*. Longman Scientific and Technical.

HEADEY, D. and FAN, S. (2008) Anatomy of a crisis: the causes and consequences of surging food prices. *Agricultural Economics*, 39, 375-391.

HOOGWIJK, M., FAAIJ, A. and EICKHOUT, B. (2005) Potential of biomass energy out to 2100, for four IPCC SRES land-use scenarios. *Biomass and Bioenergy*, 29 225-257.

HOOGWIJK, M., FAAIJ, A., VAN DEN BROEKA, R., BERNDES, G., GIELEN, D. and TURKENBURG, W. (2003) Exploration of the ranges of the global potential of biomass for energy. *Biomass and Bioenergy*, 25, 119 - 133.

HOOGWIJK, M. M. (2004) *On the global and regional potential of renewable energy sources*. RIVM, University of Utrecht.

IAASTD (2009) *International assessment of agricultural knowledge, science and technology for development: synthesis report*. Washington, DC, Island Press.

IEA (2008) *World energy outlook*. International Energy Agency (IEA).

IEA (2010) *Energy technology perspectives 2010: scenarios and strategies to 2050*. International Energy Agency (IEA), Paris.

IIASA BLS Model [Internet], available from: <www.iiasa.ac.at/Research/LUC/Research-World-food-policy/bls-model.html> [Accessed: 2011].

IPCC (2000) *Special report on emission scenarios. Intergovernmental Panel on Climate Change*. [Available from: <www.ipcc.ch/>].

IPCC (2011) *Bioenergy IN IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation*. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press.

IPCC (2007) *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*,. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

JAGGARD, K. W., QI, A. and OBER, E. S. (2010) Possible changes to arable crop yields by 2050. *Phil. Trans. R. Soc.*, 365, 2835-2851.

JOHANSSON, T. B., KELLY, H., REDDY, A. K. N. and WILLIAMS, R. H. (1993) A renewables-intensive global energy scenario (RIDGES) (appendix to Chapter-1). IN T.B. JOHANSSON ET AL (Ed.) *Renewable Energy: Sources for Fuels and Electricity*. Washington, D.C, Island Press.

JOHNSON, B. and HOPE, A. (2005) Productivity, biodiversity and sustainability. IN R. SYLVESTER-BRADLEY and J. WISEMAN (Eds.) *Yields of farmed species: constraints and opportunities in the 21st century*. Nottingham, Nottingham University Press.

JOHNSTON, M., FOLEY, J. A., HOLLOWAY, T., KUCHARIK, C. and MONFREDA, C. (2009) Resetting global expectations from agricultural biofuels. *Environ. Res. Lett*., 4

KARP, A. and SHIELD, I. (2008) Bioenergy from plants and the sustainable yield challenge. *The New Phytologist*, 179, 15.

KELLER, C. (2010) Personal communication to R. Slade (February 2010). Deputy editor F.O. Lichts.

KILPATRICK, J. (2008) *Addressing the land use issues for non-food crops, in response to increasing fuel and energy generation opportunities*. ADAS Rosemaund Ltd. [Available from: <http://www.nnfcc.co.uk/metadot/index.pl?id=8253;isa=DBRow;op=show;dbview_id=2539.>].

KORT, J., COLLINS, M. and DITSCH, D. (1998) A review of soil erosion potential associated with biomass crops. *Biomass and Bioenergy*, 14, 351-359.

KRAUSMANN, F., ERB, K.-H., GINGRICH, S., LAUK, C. and HABERL, H. (2007) Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. *Ecological Economics*.

LAUER, M. (2009) Curent terrestrial methods and activities for biomass potential assessment in Europe. *17th European Biomass Conference and Exhibition*. Hamburg, Joanneum research, institute of energy research

LEEMANS, R., VAN AMSTEL, A., BATTJES, E., KREILEMAN, E. and TOET, S. (1996) The land cover and carbon cycle consequences of large-scale utilisations of biomass as an energy source. *Global Environental Change*, 6, 335-57.

LEGG, B. J. (2005) Crop improvement technologies for the 21st century. IN R. SYLVESTER-BRADLEY and J. WISEMAN (Eds.) *Yields of farmed species: constraints and opportunities in the 21st century*. Nottingham, Nottingham University Press.

LOBELL, D. B., SCHLENKER, W. and COSTA-ROBERTS, J. (2011) Climate trends and global crop production since 1980. *Science*, 333, 616

LUDWIG, J., MARUFU, L. T., HUBER, B., ANDREAE, M. O. and HELAS, G. (2003) Domestic combustion of biomass fuels in developing countries: a major source of atmospheric pollutants. *Journal of Atmospheric Chemistry*, 44, 23-37.

LUNDQUIST, T. J., WOERTZ, I. C., QUINN, N. W. T. and BENEMANN, J. R. (2010) *A Realistic Technology and Engineering Assessment of Algae Biofuel Production*. Energy Biosciences Institute, University of California, Berkeley, California.

LUYTEN, J. (1995) *Sustainable world food production and environment*. Wageningen: AB-DLO, Delft Hydraulics.

LYND, L. R., AZIZ, R. A., CRUZ, C. H. D. B., CHIMPHANGO, A. F. A., CORTEZ, L. A. B., FAAIJ, A., GREENE, N., KELLER, M., OSSEWEIJER, P., RICHARD, T. L., SHEEHAN, J., CHUGH, A., WIELEN, L. V. D., WOODS, J. and ZYL, W. H. V. (2011a) A global conversation about energy from biomass: the continental conventions of the global sustainable bioenergy project. *Interface Focus*.

LYND, L. R. and WOODS, J. (2011b) A new hope for Africa. *NATURE 474*.

LYSEN, E., VAN EGMOND, S., DORNBURG, V., FAAIJ, A., VERWEIJ, P., LANGEVELD, H., VAN DE VEN, G., WESTER, F., VAN KEULEN, H., VAN DIEPEN, K., MEEUSEN, M., BANSE, M., ROS, J., VAN VUUREN, D., VAN DEN BORN, G. J., VAN OORSCHOT, M., SMOUT, F., VAN VLIET, J., AIKING, H., LONDO, M. and MOZAFFARIAN, H. (2008) *Biomass assessment: assessment of global biomass potentials and their links to food, water, biodiversity, energy demand and economy*. Netherlands Environmental Assessment Agency MNP.

MCLAUGHLIN, S. B. and WALSH, M. E. (1998) Evaluating environmental consequences of producing herbaceous crops for bioenergy. *Biomass and Bioenergy*, 14, 317-324.

MITCHELL, D. (2008) *A note on rising food prices* The World Bank.

MNP (2006) Integrated modelling of global environmental change: an overview of IMAGE 2.4. IN A. F. BOUWMAN, T. KRAM and K. K. GOLDEWIJK (Eds.). Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands.

MONTEITH, J. L. (1977) Climate and the efficiency of crop production in Britain [and discussion]. *Philosophical Transactions of the Royal Society of London*, 281, 277.

MONTGOMERY, D. (2007). Dirt: the Erosion of Civilizations. University of California Press.

MOREIRA, J. R. (2006) Global biomass energy potential. *Mitigation and Adaptation Strategies for Global Change*, 11, 313-342.

OFFERMANN, R., SEIDENBERGER, T., THRÄN, D., KALTSCHMITT, M., ZINOVIEV, S. and MIERTUS, S. (2010) Assessment of global bioenergy potentials. *Mitigation and Adaptation Strategies for Global Change*.

PIESSE, J. and THIRTLE, C. (2009) Three bubbles and a panic: An explanatory review of recent food commodity price events. *Food Policy*, 34 119-129.

RATHMANN, R., SZKLO, A. and SCHAEFFER, R. (2010) Land use competition for production of food and liquid biofuels: An analysis of the arguments in the current debate. *Renewable Energy*, 35, 14-22.

REN21 (2010) *Renewables 2010: global status report*. Renewable energy policy network for the 21st century (REN21).

ROKITYANSKIY, D., BENÍTEZ, P. C., KRAXNER, F., MCCALLUM, I., OBERSTEINER, M., RAMETSTEINER, E. and YAMAGATA, Y. (2007) Geographically explicit global modelling of land-use change, carbon sequestration, and biomass supply. *Technological Forecasting & Social Change*, 74, 1057-1082.

ROYAL SOCIETY (2009) *Reaping the benefits: Science and the sustainable intensification of global agriculture*. The Royal Society, London.

RUDEL, T. K., SCHNEIDER, L., URIARTE, M., TURNER, B., DEFRIES, R., LAWRENCE, D., GEOGHEGAN, J., HECHT, S., ICKOWITZ, A., LAMBIN, E. F., BIRKENHOLTZ, T., BAPTISTA, S. and GRAU, R. (2009) Agricultural intensification and changes in cultivated areas, 1970-2005. *PNAS*, 106, 20675-20680.

SCHUBERT, R., SCHELLNHUBER, H. J., BUCHMANN, N., EPINEY, A., GRIEßHAMMER, R., KULESSA, M., MESSNER, D., RAHMSTORF, S. and SCHMID, J. (2009) *Future bioenergy and sustainable land use (a report for the German Advisory Council on Global Change (WBGU)*. London and Sterling, VA, Earthscan.

SEARCHINGER, T., HEIMLICH, R., HOUGHTON, R. A., DONG, F., ELOBEID, A., FABIOSA, J., TOKGOZ, S., HAYES, D. and YU, T.-H. (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science*, 319, 1238-40.

SIMS, R., HASTINGS, A. and SCHLAMADINGER, B. (2006) Energy crops: current status and future prospects. *Global Change Biology*, 12, 2054-2076.

SINCLAIR, T. R., PURCELL, L. C. and SNELLER, C. H. (2004) Crop transformation and the challengeto increase yield potential. *Trends in Plant Science*, 9.

SLADE, R., GROSS, R. and BAUEN, A. (2011) Estimating bio-energy resource potentials to 2050: Lessons from the UK experience. *Energy and Environmental Science*, 4 2645 - 2657.

SMEETS, E., FAAIJ, A., LEWANDOWSKI, I. and TURKENBURG, W. (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. *Progress in Energy and Combustion Science*, 33 56-106.

SMIL, V. (2005) Do we need higher farm yields during the first half of the 21st century? IN R. SYLVESTER-BRADLEY and J. WISEMAN (Eds.) *Yields of farmed species: constraints and opportunities in the 21st century*. Nottingham, Nottingham University Press.

SORRELL, S. (2007) Improving the evidence base for energy policy: The role of systematic reviews. *Energy Policy*, 35, 1858-1871.

SPAROVEK, G., BERNDES, G., EGESKOG, A., FREITAS, F. L. M. D., GUSTAFSSON, S. and HANSSON, J. (2007) Sugarcane ethanol production in Brazil: an expansion model sensitive to socioeconomic and environmental concerns. *Biofuels, bioproducts and biorefining*, 1, 270-282.

SYLVESTER-BRADLEY, R., FOULKES, J. and REYNOLDS, M. (2005) Future wheat yields: evidence, theory, and conjecture. IN R. SYLVESTER-BRADLEY and J. WISEMAN (Eds.) *Yields of farmed species: constraints and opportunities in the 21st century*. Nottingham, Nottingham University Press.

THRÄN, D., SEIDENBERGER, T., ZEDDIES, J. and OFFERMANN, R. (2010) Global biomass potentials - resources, drivers and scenario results. *Energy for sustainable development* 14 200–205.

TILMAN, D., SOCOLOW, R., FOLEY, J. A., HILL, J., LARSON, E., LYND, L., PACALA, S., REILLY, J., SEARCHINGER, T., SOMERVILLE, C. and WILLIAMS, R. (2009) Beneficial biofuels-the food, energy, and environment trilemma. *Science*, 325.

TURKENBURG, W. C. (2000) *Renewable Energy Technologies: Chapter 7 of the World Energy Assessment of the United Nations*, UNDP, UNDESA/WEC. Published by UNDP, New York.

TURLEY, D. (2011) Personal communication to Raphael Slade. National Non-food Crops Centre.

UN (2007) *Coping with water scarcity: challenge of the twenty-first century - technical paper*. United Nations. [Available from: <www.worldwaterday07.org/>].

VAN VUUREN, D. P., VAN VLIET, J. and STEHFEST, E. (2009) Future bio-energy potential under various natural constraints. *Energy Policy*.

VITOUSEK, P. M., MOONEY, H. A., LUBCHENCO, J. and MELILLO, J. M. (1997) Human domination of earth's ecosystems. *Science*, 277.

VON BRAUN, J., AHMED, A., ASENSO-OKYERE, K., FAN, S., GULATI, A., HODDINOTT, J., PANDYA-LORCH, R., ROSEGRANT, M. W., RUEL, M., TORERO, M., RHEENEN, T. V. and GREBMER1, K. V. (2008) *High Food Prices: The What, Who, and How of Proposed Policy Actions* [Internet], INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE, available from: <http://www.ifpri.org/sites/default/files/publications/foodpricespolicyaction.pdf> [Accessed:

WEA (2000) *World energy assessment (WEA): Energy and the challenge of sustainability (Chapter 5: energy resources)*. UNDP, New York.

WICKE, B., SMEETS, E., DORNBURG, V., VASHEV, B., GAISER, T., TURKENBURG, W. and FAAIJ, A. (2011a) The global technical and economic potential of bioenergy from salt-affected soils. *Energy & Environmental Science*.

WICKE, B., SMEETS, E., WATSON, H. and FAAIJ, A. (2011b) The current bioenergy production potential of semi-arid and arid regions in sub-Saharan Africa. *Biomass & Bioenergy*.

WIRSENIUS, S., AZAR, C. and BERNDES, G. (2010) How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems, 103, 621-638.

WOLF, J., BINDRABAN, P. S., LUIJTEN, J. C. and VLEESHOUWERS, L. M. (2003) Exploratory study on the land area required for global food supply and the potential global production of bioenergy. *Agricultural Systems*, 76, 841-861.

YAMAMOTO, H., FUJINO, J. and YAMAJI, K. (2001) Evaluation of bioenergy potential with a multi-regional global-land-use-and-energy model. *Biomass and Bioenergy*, 21, 185-203.

YAMAMOTO, H., YAMAJI, K. and FUJINO, J. (1999) Evaluation of bioenergy resources with a global land use and energy model formulated with SD technique. *Applied Energy*, 63, 101-13.

YAMAMOTO, H., YAMAJI, K. and FUJINO, J. (2000) Scenario analysis of bioenergy resources and CO2 emissions with a global land use and energy model. *Applied Energy*, 66, 325-337.

YOUNG, A. (1998) Land resources: now and for the future, Cambridge, UK, Cambridge University Press.

YOUNG, A. (1999) Is there really spare land? A critique of estimates of available cultivable land in developing countries. *Environment, Development and Sustainability*, 1, 3-18.