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Biomass in a Low-Carbon Economy

Eric Kemp-Benedict, Sivan Kartha, and Amanda Fencl

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Resource Scarcity, Climate Change, and Business in a Finite World

Eric Kemp-Benedict[1], Sivan Kartha, and Amanda Fencl

Stockholm Environment Institute

1 Author contact: Eric Kemp-Benedict, eric.kemp-benedict@sei-international.org, 11 Curtis Avenue, Somerville, MA 02144, USA

Stockholm Environment Institute
Kräftriket 2B
106 91 Stockholm
Sweden

Tel: +46 8 674 7070
Fax: +46 8 674 7020
Web: www.sei-international.org

Head of Communications: Robert Watt
Publications Manager: Erik Willis
Editor: Marion Davis
Layout: Alison Dyke, Richard Clay

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EXECUTIVE SUMMARY

Building a low-carbon economy and reducing greenhouse gas emissions to keep climate change within relatively safe bounds will require increasing use of biomass – plant and animal materials.

Biomass is a promising source of renewable low-carbon energy, but it's not an unlimited resource: it is constrained by land and water availability, by soils' ability to produce biomass, and by the need to return some biomass to the land to retain nutrients and soil moisture. There are also competing uses for biomass: for food, for animal feed, for materials – and the need to reduce emissions constrains not only energy supplies, but also land conversion and agricultural practices. Finally, biomass is needed for natural habitat and ecosystem functioning, all the more important as ecosystems are threatened by a changing climate.

In this context, biomass is hardly a "silver bullet" – but it can be part of the solution to the low-carbon energy challenge, along with other renewable resources; greater energy efficiency; behavioural changes; and policies, industrial practices, and human settlement patterns that lead to lower carbon emissions.

Currently, the discussion of biomass resources in a low-carbon world is dominated by existing energy uses – that is, for combustion, and as feedstock for biofuels. In the long run, however, increasing electrification and new technologies could significantly reduce demand for biofuels and other liquid fuels. As this occurs, a new "bio-based economy" may emerge that focuses less on low-carbon energy and more on meeting demands from industry: for feedstocks for the production of chemicals and materials, and for combustibles for process heat. In an increasingly resource-constrained world, innovation and novelty in industrial biomass uses could spur continued economic growth.

This report, which has been written within the partnership programme between the business leaders' initiative 3C (Combat Climate Change) and the Stockholm Environment Institute, seeks to envision the future of the bio-based economy. There are multiple uncertainties, many linked to human choices – specifically, whether to act aggressively to mitigate and adapt to climate impacts, and whether to increase agricultural production. We map these different policy agendas in a scenario framework, shown in Figure E-1. In the framework we suppose that policy focus on the climate, on agriculture, or both, can be either strong or weak. This leads to four scenarios:

- **Single Bottom Line:** A world in which the main focus is on growth as usual, an economic "single bottom line". There is little attention paid to climate beyond the policies currently in the pipeline, and little interest in making agriculture more productive or sustainable.

- **Meeting the Climate Challenge:** The world adopts strong climate policies and pursues multiple options to reduce carbon emissions, including greater energy efficiency and switching to low-carbon fuels and processes. Biofuels play a prominent role, and biofuel markets drive investment and productivity improvements in agriculture, with few policy interventions.

- **Feeding the Planet:** World leaders cannot agree on strong climate policies and make only scattered efforts beyond the policies currently in the pipeline. However, public and private actors do focus intensely on feeding the world's people and follow diverse avenues to try to boost agricultural yields without seriously damaging ecosystems.

- **Sustainability Transition:** People worldwide frame their future in terms of sustainability, and see the pursuit of a bio-based economy as one way to achieve this. There is a strong policy push towards limiting human impacts on the climate while also developing a high-yielding but sustainable agriculture. In the relatively short time of the scenario, only the first steps can be taken toward such a transition, but by 2035 it is clear that a sustainability transition is possible.

The goal of avoiding dangerous climate change is achievable, though challenging. While this is best shown from a full technological assessment, such as the International Energy Agency's *Energy Technology Perspectives* (IEA 2010a), we make the point with the emissions abatement cost curves computed by Vattenfall with McKinsey & Company (3C 2007), which have since been updated by McKinsey (2009).

Nearly one-third of the total mitigation potential by 2030 that McKinsey identifies would be in the forest and agriculture sectors. To this, one can add the further mitigation potential from biomass outside

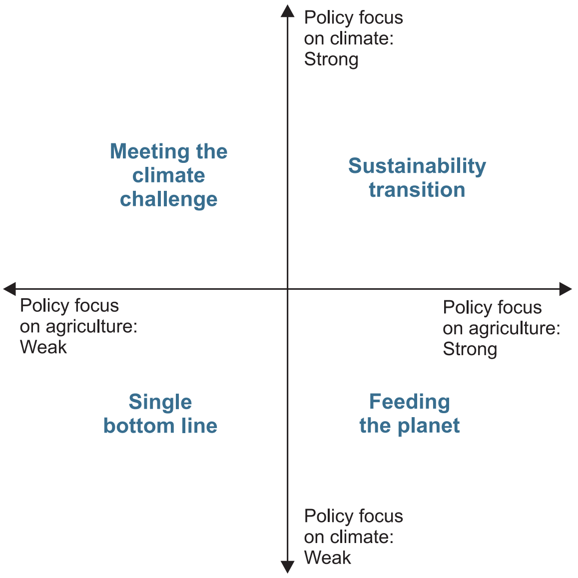

Figure E-1: Scenario framework, with the location of the four scenarios

of the forest and agriculture sectors – for biofuels (for the transport sector) and biopower (for the electric sector). The 3C Roadmap suggests that these reductions can be realised through a combination of a carbon price, minimum energy and carbon efficiency standards, and an international effort to achieve emissions reductions in the forestry and agriculture sectors, combined with public support for specific low-emitting technologies in order to bring the costs at the high end of the cost curve down.

THE BIO-BASED ECONOMY

Plants are remarkable and unique chemical factories. Photosynthesis is the only process known to break the chemical bonds in carbon dioxide at ambient or moderate temperature and pressure. Once the bonds are broken, plants (or, more generally, primary producers, which construct living matter from non-living matter), construct complex carbon compounds with stable, high-energy bonds. Then they, and other living things, use those compounds for energy, nutrients, and structural materials. Indeed, all of the complex carbon compounds in today's economy, including fossil carbon, are ultimately derived from a product of photosynthesis, whether directly, as with wheat grain, cotton fibre, and palm oil, or indirectly, as with cellophane, gasoline, and synthetic plastics.

For this report, we define a *bio-based economy* as a system of production and consumption for human needs in which materials are composed almost entirely of biologically derived materials and abundant or easily recyclable mineral resources (such as steel, cement, and glass). In such an economy, currently petroleum-derived materials, such as transportation fuels and plastics, are replaced by materials derived from biological carbon sources. Also, technologies requiring rare mineral resources may be partially replaced by carbon-based materials such as organic conductors.

It must be stressed that simply using biomass as a source does not guarantee net zero or negative greenhouse gas emissions, and the low-carbon economy constrains biomass production to certain types of land conversion and certain agricultural practices. If land with high carbon density is converted to biomass production at a lower carbon density, there will be a one-time release of carbon when the land is cleared and replanted. Also, some agricultural inputs emit greenhouse gases when they are produced, and some agricultural practices result in emissions of nitrous oxide or methane, both potent greenhouse gases.

LIMITS TO BIOMASS PRODUCTION

Biomass is a renewable, but limited resource. Like surface water, it regenerates naturally, but at any given moment only a finite amount is available. Also like water, the resource can become degraded through human action and lose some of its regenerative capacity. Estimates of bioenergy potential are sensitive to numerous assumptions, many of which are subject to large and irreducible uncertainty. Offermann *et al.* (2010) assessed 19 studies of long-term prospects for bioenergy production worldwide, and found an enormous diversity of estimates, ranging from zero to 1,548 exajoule per year (more than three times today's global primary energy supply). Within this broad range one finds a degree of convergence, with half the estimates falling between 162 and 297 exajoule per year in 2050, which is between 33 and 60 per cent of current global energy consumption, from IEA statistics (IEA 2008). However, sustainability constraints shift the estimate toward the lower end of this range.

The main determinant of energy crop estimates is the available land, which in turn is sensitive to assumptions about population growth, diet (especially meat consumption), and crop yield improvements. Also, it is widely recognised that real-world results depend on factors beyond biophysical parameters, such as economic trade-offs between

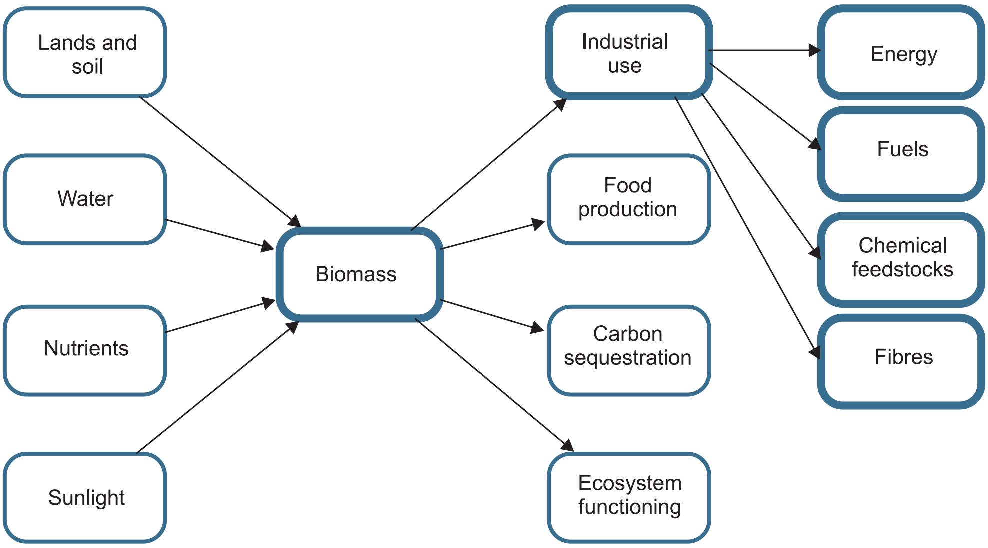

Figure E-2: Biomass in the economy

energy feedstocks, cash crops, and food production, and political, economic and cultural factors.

BOOSTING PRODUCTION

In already high-yielding areas, the potential to improve crop yields may be limited, and yield increases have slowed and plateaued in many countries in recent years. Broadly, strategies to boost productivity focus both on increasing the yield potential – yield under ideal conditions, with no limits on water or nutrients, and effective control of pests, disease, or other stresses – and shrinking the gap between potential and actual yields.

The dramatic increases in yields of wheat, barley, and rice, three major "Green Revolution" crops, were mainly the result of shifting plant biomass to the grain rather than to stems and leaves – a strategy that favours food production but doesn't increase total biomass production. Today, light utilisation (photosynthesis) is seen as the most promising target for breeding and genetic modification to further increase yield potential and total biomass production. Some have estimated that with an active research programme, plants with up to 20 per cent higher photosynthetic efficiency could be in farmers' fields within 25 years.

Still, soils, climate, and slope may not be ideally suitable for a given crop, so realised yields may be somewhat below yield potential, even if all other stresses – such as pests and diseases – are effectively controlled. This means more land is likely to be needed, and FAO estimates suggest that highly productive land is already occupied, so any expansion will be onto less productive land.

SCENARIO OUTCOMES

Our analysis shows that while the Meeting the Climate Challenge scenario keeps cumulative emissions to 1,000 Gt CO_2 by 2035, it requires annual emissions to drop to zero in 2036, or net negative emissions later in the century. In contrast, the Sustainability Transition scenario seeks to meet climate mitigation targets soon, with sharply reduced annual emissions by 2020 and slow growth in cumulative emissions. Nevertheless, total demand for biomass is not much greater: a combination of low total energy consumption and lower meat consumption keeps total biomass requirements in check, despite a larger share of biomass in total energy supply (25 per cent in 2035, versus 13 per cent in the Meeting the Climate Challenge scenario). As shown in Figure E-3, food consumption dominates human use of biomass in all scenarios, but biomass use for both energy and chemicals increases.

In terms of agricultural land use, three of the four scenarios lead to similar increases. However, in the Sustainability Transition, that is partly because some productive agricultural land is given up to restore ecosystems, and some potential yield increases are sacrificed for a smaller environmental impact. At the same time, the Sustainability Transition helps meet the climate challenge through carbon sequestration

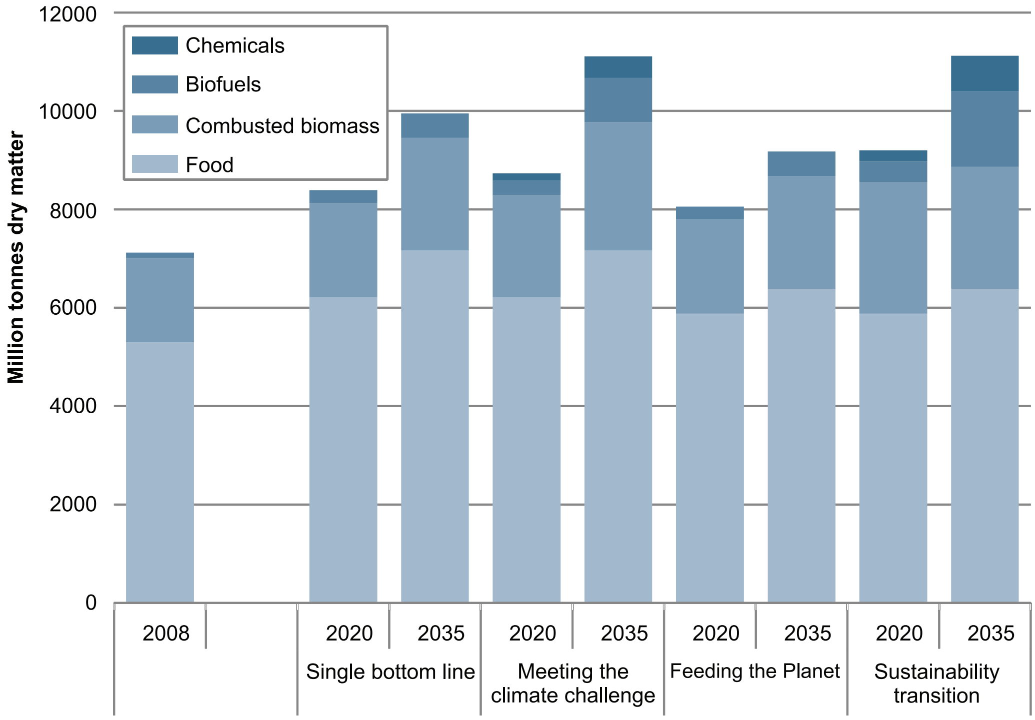

Figure E-3: Use of biomass in the scenarios

and supplying feedstock for biofuels and combustible material for electricity and heat production. In contrast, the Feeding the Planet scenario only seeks to improve agricultural output while lessening agriculture's impact, which leads to a strong reduction in agricultural footprint. In the Meeting the Climate Challenge scenario, the world reduces carbon emissions, but humanity's agricultural footprint increases through moderate increases in biofuels production and much more significant increases in food production with only modest increases in yields. The Single Bottom Line scenario, while perhaps most aligned with current political realities, may ultimately undermine itself; people can change the boundaries of what is politically realistic, but not the physical boundaries of the earth's safe operating space.

Our analysis suggests that while no one path is perfect – and most would put more pressure on the land – a "Sustainability Transition", combined a focus on both agricultural production and climate mitigation, could yield great benefits: It would help address the urgent climate problem, and spur improvements in agriculture that would supply food for our growing population and new agricultural products. The transition could also spur innovation – if we encourage the use of bio-materials, then entrepreneurs and businesses can take this on as a challenge, and thrive on it. And in the long run, we will be building a solid and sustainable foundation for our future economy.

1 INTRODUCTION

Building a low-carbon economy and reducing greenhouse gas emissions to keep climate change within relatively safe bounds will require increasing use of biomass – plant and animal materials.

Biomass is a promising source of renewable low-carbon energy, but it is multiply constrained. It is constrained by land and water availability, by soils' ability to produce biomass, and by the need to return some biomass to the land to retain nutrients and soil moisture. Also, people need biomass for food, and to feed their livestock; they already use it for materials, and may need it more if biomass becomes the basis of a post-petroleum chemical industry. Additionally, the goal to reduce greenhouse gas emissions itself constrains not only energy supplies, but also land conversion and agricultural practices, potentially influencing yields. Finally, biomass is needed for natural habitat and ecosystem functioning – needs that will themselves evolve as ecosystems are threatened by a changing climate.

Indeed, humanity is already placing multiple pressures on the global environment that have crossed, or threaten to cross, the planet's "safe operating space" (Rockström *et al*. 2009). Anthropogenic climate change is a prominent example, but several others – biodiversity loss, the nitrogen cycle, phosphorous use, and land use change – are intimately connected to agriculture. One can safely conclude that biomass will not provide a "silver bullet" solution to the low-carbon energy challenge. Biomass energy can, however, provide parts of a solution that also involves other renewable resources; greater energy efficiency; behavioural changes; and policies, industrial practices, and human settlement patterns that lead to lower carbon emissions.

A BIO-BASED ECONOMY

Understandably, the discussion of biomass resources in a low-carbon world is dominated by existing energy uses – that is, for combustion, and as feedstock for biofuels (e.g., Brehmer *et al*. 2009). Both of those uses are likely to continue for the near future, but in the long run, increasing electrification and new technologies could significantly reduce demand for biofuels and other liquid fuels for many – although not all – transport needs (Heaps *et al*. 2009).

There is an important distinction between those two uses – carbon for energy and carbon for chemicals and materials. People want the services that energy provides, rather than a particular energy carrier, and efficiency improvements can provide the same level of services from less energy (IEA 2010a). Also, energy can be produced from diverse sources –wind, hydropower, solar, biomass, fossil fuels – and even cars can be powered either by liquid fuels or by electricity from the grid. The carbon compounds in chemical feedstocks, meanwhile, are much more difficult to substitute (Ayres 2007). Much of the mass of the carbon in chemical feedstock ends up in the final product – in plastic, rubber, cellophane, and carbon fibres. There are opportunities to improve material use efficiency and substitute materials, but they are limited compared to the potential to increase energy efficiency and substitute energy sources.

In the future, as demand for biofuels wanes and other renewable energy sources proliferate, our use of limited biomass resources may change significantly. The bio-based economy, initially geared to meeting a need for low-carbon energy, may shift its focus to meeting demands from industry. Industrial demands may include both higher-valued feedstocks for the production of chemicals and materials, and combustibles for process heat. In a still longer run, economic expansion supported by constrained resources could push economies onto a track of steady and strong dematerialisation, facilitated by a shift towards services (Ayres and van den Bergh 2005). In such an economy, growth through innovation and novelty in the chemical sector could eclipse growth through expanded production.

Thus, to understand the future of the bio-based economy, it is important to look beyond our immediate need to use biomass to help reduce carbon emissions.

SCENARIOS OF BIOMASS PRODUCTION AND USE

There are multiple uncertainties about the future of biomass production and consumption. Many have to do with human choices – specifically, whether to act aggressively to mitigate and adapt to climate impacts, and whether to increase agricultural production. As Foley *et al*. (2011) note, increasing agricultural production while reducing its footprint is not only necessary, but possible, and it can also be made more resilient to the impacts of climate change, as described in Vermeulen *et al*. (2011).

We map these different policy agendas in a scenario framework, shown in Figure 1. In the framework we suppose that policy focus on the climate, on agriculture, or both, can be either strong or weak. Figure 1 shows the following four scenarios:

- **Single Bottom Line:** A world in which the main focus is on growth as usual, an economic "single bottom line". There is little attention paid to climate beyond the policies currently in the pipeline, and little interest in making agriculture more productive or sustainable.

- **Meeting the Climate Challenge:** The world adopts strong climate policies and pursues multiple options to reduce carbon emissions, including greater energy efficiency and switching to low-carbon fuels and processes. Biofuels play a prominent role, and biofuel markets drive investment and productivity improvements in agriculture, with few policy interventions.

- **Feeding the Planet:** World leaders cannot agree on strong climate policies and make only scattered efforts beyond the policies currently in the pipeline. However, public and private actors do focus intensely on feeding the world's people and follow diverse avenues to try to boost agricultural yields without seriously damaging ecosystems.

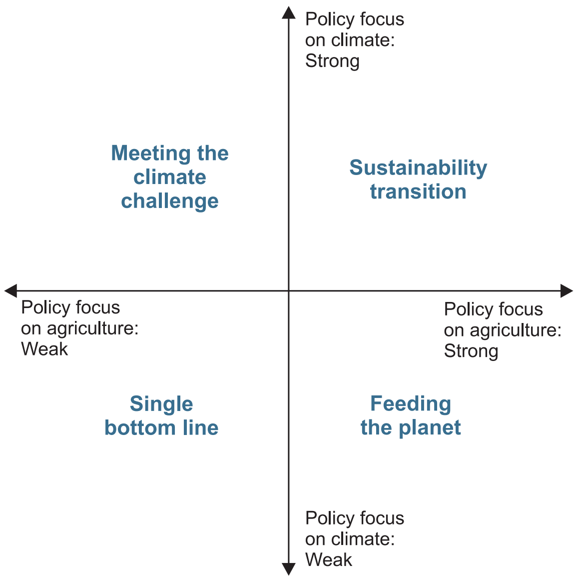

Figure 1: Scenario framework, with the location of the four scenarios

- **Sustainability Transition:** People worldwide frame their future in terms of sustainability, and see the pursuit of a bio-based economy as one way to achieve this. There is a strong policy push towards limiting human impacts on the climate while also developing a high-yielding but sustainable agriculture. In the relatively short time of the scenario, only the first steps can be taken toward such a transition, but by 2035 it is clear that a sustainability transition is possible.

2 THE LOW-CARBON AND BIO-BASED ECONOMIES

This report focuses on the role of biomass in an effort to bring the world onto a low-carbon path to reduce the chance of dangerous climate change. We argue that substantially increasing the role of biomass in a *low-carbon* economy will set the stage for a *bio-based* economy. At a minimum, a low-carbon economy will require some features of a bio-based economy. In this section we define what we mean by these two economies and outline their boundaries.

THE LOW-CARBON ECONOMY

Responding to scientific assessments of the risk of dangerous climate change, the 3C initiative recommends in its Roadmap that governments set emissions targets consistent with a global temperature increase of less than 2°C above pre-industrial levels by the end of the century (3C 2007). There is no unique emissions pathway that can achieve this goal. The most that can be said, based on current understanding of the climate system, is that a given path has a certain probability of keeping warming below 2ºC. For this report, we define a *low-carbon economy* as a system of production and consumption for human needs that limits net greenhouse gas (GHG) emissions enough to achieve a 75 per cent probability of restraining the global temperature increase by 2100 to less than 2°C. According to the nomenclature adopted by the Intergovernmental Panel on Climate Change (IPCC 2007), such a pathway can be said to be "likely" to keep warming below 2ºC, but not "very likely". A recent assessment suggests that this goal is consistent with cumulative carbon dioxide emissions of 1,000 gigatonnes ($GtCO_2$) between 2000 and 2049 or, when considering all greenhouse gases, the equivalent of 1,500 gigatonnes of carbon dioxide ($GtCO_2e$) (Meinshausen *et al*. 2009).

As the 3C Roadmap argues, the goal of avoiding dangerous climate change is achievable, though challenging. While this is best shown from a full technological assessment, such as the International Energy Agency's *Energy Technology Perspectives* (IEA 2010a), we join the Roadmap in making the point with the emissions abatement cost curves computed by Vattenfall with McKinsey & Company (3C 2007), which have since been updated by McKinsey (2009).

The McKinsey study identifies abatement options that cost less than 60 EUR per tonne CO_2e. It finds that with these options, emissions can be reduced by 38 million tonnes of CO_2e per year by 2030, below a business-as-usual trajectory of 70 million tonnes of CO_2e per year. McKinsey estimates that this will bring emissions to the upper end of the range of trajectories consistent with our definition of a low-carbon economy. To bring emissions comfortably within the range, and the planet within a safe operating space, requires the costlier options identified by McKinsey, in the range of 60-100 EUR per tonne CO_2e.

We note that nearly one-third of the total mitigation potential by 2030 that McKinsey identifies would be in the forest and agriculture sectors. To this, one can add the further mitigation potential from biomass outside of the forest and agriculture sectors – for biofuels (for the transport sector) and biopower (for the electric sector). The 3C Roadmap suggests that these reductions can be realised through a combination of a carbon price, minimum energy and carbon efficiency standards, and an international effort to achieve emissions reductions in the forestry and agriculture sectors, combined with public support for specific low-emitting technologies in order to bring the costs at the high end of the cost curve down.

THE BIO-BASED ECONOMY

Plants are remarkable and unique chemical factories. Photosynthesis is the only process known to break the chemical bonds in carbon dioxide at ambient or moderate temperature and pressure (Ayres 2007). Once the bonds are broken, plants (or, more generally, primary producers, which construct living matter from non-living matter), construct complex carbon compounds with stable, high-energy bonds. Then they, and other living things, use those compounds for energy, nutrients, and structural materials. Indeed, all of the complex carbon compounds in today's economy, including fossil carbon, are ultimately derived from a product of photosynthesis, whether directly, as with wheat grain, cotton fibre, and palm oil, or indirectly, as with cellophane, gasoline, and synthetic plastics.

For this report, we define a *bio-based economy* as a system of production and consumption for human needs in which materials are composed almost entirely of biologically derived materials and abundant or easily recyclable mineral resources (such as steel, cement, and glass). In such an economy, currently petroleum-derived materials, such as transportation fuels and plastics, are replaced by materials derived from biological carbon sources. Also, technologies requiring rare mineral resources may be partially replaced by carbon-based materials such as organic conductors.

Biomass can help meet our urgent need for a low-carbon economy. However, the long-term value of a bio-based economy is much greater: long-term sustainability requires renewable sources of materials, and biomass is one of the few good options.

3 BIOMASS AND THE LOW-CARBON ECONOMY

The output of the world's current primary producers and the other living things that they support is collectively termed "biomass". Visions of the bio-based economy (Clark and Deswarte 2008; Langeveld *et al.* 2010; Klass 1998; Mathews 2009) assume almost complete dependence on plant materials, in particular carbohydrates, to the point that the bio-based economy has been termed the "carbohydrate economy", in contrast to today's "hydrocarbon economy" (Morris 2006). For this report we define *biomass* as the carbon and chemical energy stored in living and non-decayed dead plant matter.

The term "low-carbon economy" is evocative, and we use it in this report and have given it a working definition, but it is potentially misleading. As we have defined it and as others use it, the name is shorthand for an economy that contributes substantially less than today's economy to the accumulation of greenhouse gases in the atmosphere, even though a low-carbon economy may nevertheless have considerable carbon flows if it grows and consumes plant matter as raw material. The reason why an economy that relies heavily on biomass can be low-carbon is that biomass is produced by fixing atmospheric carbon, and so it has the potential to be net neutral, or a net sink, for carbon dioxide. Indeed, for most of human history, economies and energy production were heavily carbon-based, with clothing, nets and ropes, containers, building materials, combustibles, and traction supplied predominantly by plants, animals, and their wastes, yet without contributing to a significant rise in atmospheric concentrations of carbon dioxide.

However, it must be stressed that simply using biomass as a source does not guarantee net zero or negative greenhouse gas emissions, and the low-carbon economy constrains biomass production to certain types of land conversion and certain agricultural practices. While many aspects of pre-industrial economies were carbon-neutral, large-scale forest clearing may have released enough carbon into the atmosphere to keep the earth warmer than it would otherwise have been (Vavrus *et al.* 2008; Ruddiman and Ellis 2009). And with modern biofuel cycles, it is generally the case that if land with high carbon density is converted to biomass production at a lower carbon density, there will be a one-time release of carbon when the land is cleared and replanted. In the well-studied case of palm oil plantations on peatlands, the net emissions were shown to be very large (Börjesson 2009; Wicke *et al.* 2008). Also, some agricultural inputs emit greenhouse gases when they are produced, and some agricultural practices result in emissions of nitrous oxide or methane, both of which are potent greenhouse gases. Averaged over a century, nitrous oxide is 300 times more effective, and methane 25 times more effective, than carbon dioxide at trapping heat in the atmosphere (Hoefnagels *et al.* 2010), and in some biofuel cycles, these are major contributors to the overall greenhouse gas balance.

THE RESOURCE: CARBON FIXATION AND ALLOCATION IN PLANTS

Plants fix atmospheric carbon and then allocate it to various uses. Some is stored in chemical constituents – carbohydrates, lipids, proteins, and other compounds – some is consumed for plant functions – respiration – and some is allocated to plant symbionts, such as fungi that help plants access nutrients in the soil. An understanding of carbon allocation within plants is essential to understanding the supply of biomass to a bio-based economy.

Ultimately, the amount of carbon a plant has to allocate is determined by the rate at which it fixes carbon from the atmosphere through photosynthesis. In the process, energy in sunlight is stored as chemical energy in the plant, some of which is used for plant metabolism and symbiotic organisms, and some of which is available as food or materials for humans and other animals. Different carbon pools in plants are the raw materials from which the feedstocks of bio-based economy derive, and are described in Annex 1. There are many potential commercial uses of these biological constituents – in industry, for households, in the transport sector, for textiles, packaging, and other purposes (Werpy and Petersen 2004).

Observed rates of carbon fixation are well below the theoretical maximum, and also well below the highest rates of carbon fixation in some photosynthetic organisms. The gap between the theoretical potential and observed rates offers the hope that with good management, crop breeding, and genetic modifications, future researchers and farmers may significantly raise dry matter productivity. Because carbon fixation is the essential constraint on biomass supplies, increasing the rate of dry matter production is one of the few strategies to raise global biomass potential. However, many factors – such as climate, shading, pests, disease, preferences for specific crops, and steepening marginal costs with each productivity gain – will likely limit the maximum achievable dry matter yields to well below the theoretical potential.

Some of the carbon fixed by primary producers is stored in the soil. Soils are important stores of carbon, and strategies for a low-carbon world include increasing soil carbon; to the extent that soil carbon is increased by directing more of the carbon fixed by plants into the soil, it will compete with the goal of maximising above-ground carbon for industry and agriculture. In soils, carbon is transferred from plants and their associated fungi to leaf and stem litter and soil microbes, followed by deposition into one of several soil organic carbon pools. In the process, plants, fungi, and microbes release carbon dioxide and methane from respiration. Soil carbon can remain stored in different pools with widely varying times, ranging from months to years to centuries (Falloon and Smith 2009). Climate-mitigation strategies that rely on soil carbon storage seek to maximise the flow of carbon into longer-lived pools (although build-up of the longest-lived pools is slow) or to stabilise the carbon stored in shorter-lived pools (Lal 2008).

LIMITS TO BIOMASS PRODUCTION

Biomass is a renewable, but limited resource. Like surface water, it regenerates naturally, but at any given moment only a finite amount is available. Also like water, the resource can become degraded through human action and lose some of its regenerative capacity. There have been several attempts to estimate global and regional biomass production potential. We review the more prominent and recent estimates in this section.

Human appropriation of net primary production

One way to gauge biomass production potential is to look at what share of the earth's biological production already goes to human use – a measure called "human appropriation of net primary productivity" (HANPP). The first major HANPP study was that of Vitousek *et al.* (1986), and the most recent major assessment was that of Imhoff *et al*. (2004). Despite nearly two decades between these two studies, the method that Vitousek *et al*. pioneered is essentially the same as that used in later studies (Haberl 2007; Imhoff *et al.* 2004; Rojstaczer *et al.* 2001). The main innovation is that NPP can now be partly estimated from satellite data.

Imhoff *et al.* estimated a range of values for global HANPP of terrestrial biomass, from a low estimate of 14 per cent, through an intermediate estimate of 20 per cent, to a high estimate of 26 per cent. The difference in the values is due to different assumptions for rates of appropriation and losses. The authors point out that substantial gains can be achieved with harvest and storage technology that reduces losses. Regionally, Imhoff *et al.*'s intermediate HANPP estimates vary from 6 per cent in South America to 80 per cent in South Central Asia. Within high-income regions, the value for Western Europe is 72 per cent, and for North America, 24 per cent. There is clearly a wide variation in the level of pressure on ecosystems. However, these values should be interpreted with caution, because the NPP that is being appropriated in Western Europe and North America (or any other region) is not entirely derived from that region. For example, China has an active wood-processing industry, but the raw material comes mainly from other countries (Katsigris *et al*. 2004). Regional values show how local "footprints" may exceed local resources, but in a world connected by trade, the global average is a better indicator of pressure on ecosystems.

Estimates of HANPP cover a broad range, but Imhoff *et al*. (2004) give an intermediate estimate of 20 per cent. While there is no specific value for HANPP that is "too high", there is evidence that higher HANPP tends to impair ecosystem functioning (Haberl 2007). Also, as a measure of human impact on the environment, 20 per cent is clearly large; if all NPP were provided by a single type of plant, then at this rate two out of every ten plants would be dedicated to a single species – humans. Although those plants would also support other species, such as pollinators, symbionts, and what people consider pests, with about 9 million eukaryote species on the planet (Sweetlove 2011), this is an astonishingly high rate of appropriation. Thus the HANPP estimates suggest that biomass is already in heavy use by humans. A bio-based economy may be necessary for long-term sustainability, but it will have to be developed carefully to avoid stressing resources beyond their capacity to renew themselves.

Bioenergy potential

Estimates of bioenergy potential are sensitive to numerous assumptions, many of which are subject to large and irreducible uncertainty. Worse, in many studies the assumptions are implicit rather than explicit, so that bioenergy estimates are notoriously ambiguous.

A comprehensive review carried out by Offermann *et al*. (2010) assessed 19 studies of long-term prospects for of bioenergy production worldwide. The most striking result of the study is the enormous diversity of estimates, ranging from zero to 1,548 exajoule per year (more than three times today's global primary energy supply). Within this broad range one finds a degree of convergence, with half the estimates falling between 162 and 297 exajoule per year in 2050, which is between 33 and 60 per cent of current global energy consumption, from IEA statistics (IEA 2008). However, sustainability constraints shift the estimate toward the lower end of this range.

There are two major classifications of bioenergy feedstocks: purpose-grown energy crops, and residues from other activities such as agriculture, forestry, food production and waste management. The potential for energy crops is widely estimated to be far greater than for residues: Among the estimates for 2050 reported above, energy crops comprise a range of zero to 1,272 exajoule per year, while residues would provide only 62 to 325 exajoule per year.

The main determinant of energy crop estimates is the available land, which in turn is sensitive to assumptions about population growth, diet (especially meat consumption), and crop yield improvements. In the studies assessed by Offermann *et al.*, the land area assumed to be available for energy crop production ranged from zero to 7 billion hectares, with a modest convergence in the range of 2 to 3 billion hectares. The available land is presumed to come primarily from surplus agricultural land, although some studies estimate that lower-quality abandoned and degraded land could provide an additional 580 million hectares.

Most studies do not disaggregate their estimates by geographic region. Neglecting region-specific assumptions about key parameters such as yields can overestimate the potential by 100 to 150 per cent (Johnston *et al*. 2009). The few studies that carried out regional analyses have found most of the world's bioenergy potential to be in developing countries, although the actual magnitudes are highly sensitive to assumptions about crop yields and trade flows.

Offermann *et al*. stress that few studies consider agro-ecological changes caused by climate change, water scarcity, excessive degradation, or biodiversity constraints. They note that one analysis, when redone by its authors to account for water scarcity, degradation, and biodiversity constraints, resulted in the original estimate being reduced by one-third. Analyses not included in the Offermann *et al*. review that did take such factors into account generated low estimates; for example, Beringer and Lucht (2010) find between 39 and 125 exajoule per year of bioenergy crop potential.

Although bioenergy potential analyses do not take such factors into account, it is widely recognised that real-world results depend on factors beyond biophysical parameters, such as avoiding competition between energy feedstocks and food production (Rathmann *et al*. 2010), and political, economic and cultural factors (Johnston *et al*. 2009).

This review of estimates of bioenergy potential makes clear that there is a great deal of uncertainty about the size of the potential resource. Despite the uncertainty, it seems likely that the lower, rather than higher, bioenergy estimates are more realistic. Also, the stresses that people have been placing on ecosystems have already degraded the resource. Future scenarios for a bio-based economy should take into account both the uncertainties and the likelihood of continuing constraints and increasing stress.

THE LOW-CARBON, BIO-BASED ECONOMY: A CONSTRAINED BUT PROMISING FUTURE

Uses of biomass are illustrated in Figure 2. As shown in the figure, biomass production requires land and its associated soils, water, nutrients, and sunlight. The biomass itself can then be used as industrial products or feedstocks, or for food and animal feed. As indicated above, it can also be used for carbon sequestration (or misused to release stored carbon). Finally, biomass is essential for ecosystem functioning; primary producers are the basis of all food webs, and plants provide supporting and regulating ecosystem services, in addition to the cultural and provisioning services that humans enjoy directly.

The competing demands illustrated in Figure 2 show that biomass is multiply constrained. It is promising both for immediate actions to reduce carbon emissions, and also as an important source of materials for a long-term sustainable future; but annual production is limited, and needs are high.

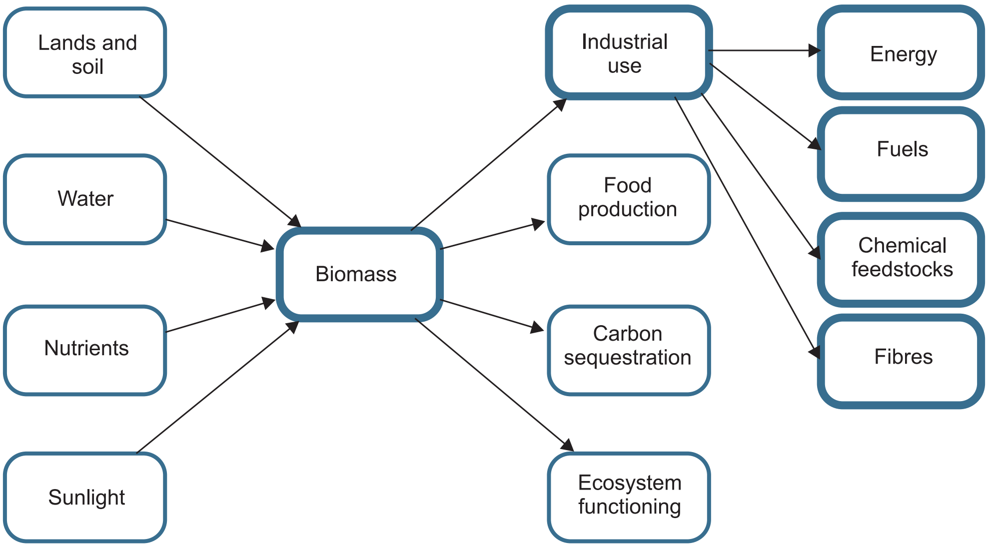

Figure 2: Biomass in the economy

4 THE FUTURE OF INCREASING YIELDS

The dramatic increases in yields of wheat, barley, and rice, three major "Green Revolution" crops, were mainly the result of shifting plant biomass to the grain rather than to stems and leaves (Evans 1998; Foulkes *et al*. 2009). The ratio of grain (or, more generally, the "economic portion" of the plant) to total above-ground dry matter is called the harvest index. Harvest indices in cereal crops today are around one-half, compared to around one-third before the start of the Green Revolution. In contrast, total dry matter production – primary production – in field crops has hardly changed (Evans 1998).[1] This is a sobering insight for the bio-based economy, which intends to use as much of the plant as possible. While there are alternative routes to increasing yields, which we explore in this section, the truly astounding yield growth of the Green Revolution cannot be taken as representative of future yield growth, because the rise in grain yields came at the expense of cellulosic biomass. Thus, biomass production in the past half-century has been characterised by a relatively constrained total amount of dry matter and considerable success in changing allocations to different components.

Even for grain yields, future gains may be slower than in the past (Lobell *et al*. 2009). While a scenario from the mid-1990s (Waggoner 1995) anticipated that a great deal of land could be "spared for nature" through yield increases, even with a world population of 10 billion, a more recent assessment (Balmford *et al*. 2005) reaches a different conclusion, that cropland area in 2050 will be higher than it is today, even with continued increases in yields, while the Food and Agriculture Organization of the United Nations, in its report *World Agriculture: Towards 2030/2050*, states about cereals that "land and water resources are now more stretched than in the past and the potential for continued growth of yield is more limited" (FAO 2006). These trends do not necessarily reflect biological constraints. Apparent yield plateaus in high-income countries may be the result of policy rather than agronomic constraints (Finger 2010; Peltonen-Sainio *et al*. 2009), and given continued advances in agronomic and breeding techniques, further linear increases in yields may be a reasonable assumption (Ewert *et al*. 2005). However, slowing yield growth in high-yield developing countries is a real and well-documented problem. Spiertz and Ewert (2009) report that wheat yield increases are stagnating in the Indo-Gangetic Plains, while rice yields are declining due to climatic factors (Pathak *et al*. 2003) and diminishing response of cereals to external inputs (Kalra *et al*. 2007). Tilman *et al.* (2002), in a review, highlight the problem of stagnating yields in major rice-producing developing countries.

A further difference from the past is that the scale of human impact on the environment and the size of human populations have both grown considerably since the middle of the last century (Steffen *et al*. 2007). Thus the scope for action is more constrained than in the past. Future yield increases must be sustainable (Foley *et al*. 2011; Sinclair *et al*. 2004; Balmford *et al.* 2005; Tilman *et al*. 2002), but cannot use the lowest-impact, lowest-input approaches if we are to produce both food and fuel (Sadras *et al*. 2009). They must also be tuned to the progressive climate change anticipated over the next century (Vermeulen *et al*. 2011).

As a counterpoint to these dampening observations, the yield increases of the Green Revolution largely bypassed Sub-Saharan Africa (Evenson and Gollin 2003) and many parts of Asia. Thus in these regions there is considerable scope for raising yields (Diao *et al*. 2008); indeed, some gains can be made by encouraging the adoption of existing, but under-used varieties (Janaiah *et al*. 2005).

YIELD POTENTIAL

Broadly, strategies to raise yields focus both on increasing the yield potential – yield under ideal conditions, with no limits on water or nutrients, and

1 Important regional differences and changes in breeding strategy over time modify this broad statement. Slafer and Andrade (1991), in a global survey of bread wheat, conclude that roughly one-half of yield increases was due to technical improvements, and the other half to genetic improvements, of which almost the entire gain was from an increase in harvest index. Hay (1995) cites evidence for wheat that in Northern Europe nearly all of the increase was due to rising harvest index; in Australia, roughly 20 per cent was from rising biomass yield; and in Canada, most of the increase was due to increasing biomass production. For rice, Peng *et al*. (2000) grew cultivar lines that were developed between 1966 and 1995 under identical conditions. They found that for cultivar lines developed before 1980, the most systematic contribution to rising yields came from an increase in the harvest index, and after 1980 from increasing dry matter production. These two periods differed in other ways as well, and were labeled the "early" and "late" Green Revolutions by Evenson and Gollin (2003). Maize and soybean yields mainly grew through increasing biomass production (Foulkes *et al*. 2009).

effective control of pests, disease, or other stresses (Evans and Fischer 1999) – and shrinking the gap between potential and actual yields. As yield is strongly influenced by environmental factors, effective breeding and genetic engineering strategies target physiological traits that are associated with higher yield potential, rather than yield per se; selecting for high yield potential is effective except in highly stressed environments, where selection for stress tolerance shows better results (Foulkes *et al*. 2009; Evans and Fischer 1999).

Because carbohydrates are the least-costly chemical components in plants (measured in molecules of glucose), followed by lignin (Poorter and Villar 1997), the most efficient use of fixed carbon is carbohydrate and ligno-cellulosic biomass – that is, stems, leaves, stores of sugar and starch, and woody trunks – which will form the basis of so-called "second-generation" biofuels (Naik *et al*. 2010; Somerville *et al*. 2010). Feedstock production for first-generation biofuels – sugar, starch, and oil crops – and chemicals derived from sugars, starches, and lipids can directly benefit from the dominant Green Revolution yield-boosting strategy. Second-generation feedstocks and biorefineries, which make use of most of the plant material, can also benefit, but not directly. Production for the second-generation feedstocks themselves must focus on increasing total biomass yield, but to the extent that food crops and first-generation feedstocks are competing for land with second-generation feedstocks, any efforts to increase harvest index will reduce the total land area required for both food and fuel.

Yield potential y_p for field crops can be calculated as total biomass potential B_p multiplied by three factors: the fraction χ of the available growing time that is devoted to the crop; the fraction α of the total biomass that is above ground, and the harvest index, η, [2]

$$y_p = \eta \alpha \chi B_p. \qquad (1)$$

2 This equation differs slightly from the conventional definition of yield potential, which focuses on above-ground biomass and one growing season (Long *et al*. 2006). In the context of climate mitigation, below-ground biomass is important, while the factor χ conveniently captures the yield benefits of multiple cropping. We specify above-ground biomass because, like most global biomass assessments, we focus on cereals, oil-crops, pulses, and grasses in this report. By weight, root crops contribute just under one-half as much as cereals to diets (FAO 2010), but much of the weight is water; on a calorie basis, root crops contribute one-tenth as much as cereals.

The factors in this equation correspond to the way that the characteristics of crop varieties are monitored and reported. The harvest index is a largely heritable trait (Hay 1995). Partitioning of fixed carbon between above and below-ground is more variable, but except in water-stressed areas crops typically allocate a relatively high proportion of carbon above ground (Foulkes *et al*. 2009). The fraction of the available growing time devoted to the crop is related to the cropping intensity, or the number of crops per year on the same land, which is in turn related to heritable traits controlling the time it takes a plant to fully mature.

Biomass potential B_p is determined by the total amount S of photosynthetically active sunlight received over the growing period, and the efficiencies of light interception ε_i, and light utilisation ε_u (Long *et al*. 2006). A factor k converts from light energy to tonnes of carbon in biomass,

$$B_p = kS\varepsilon_i\varepsilon_u. \qquad (2)$$

Radiation interception and harvest index appear to be approaching their limit in modern grain cultivars. Harvest index in cereals was estimated to have a peak value of 0.62 (Austin 1980); as some crops have actually exceeded this limit, although barely, it seems that there is little scope for improvement (Hay 1995; Slafer and Andrade 1991). Because radiation interception is also already highly efficient in modern varieties, light utilisation – photosynthesis – is the most promising target for breeding and genetic modification to increase yield potential (Foulkes *et al*. 2009; Long *et al*. 2006; Beadle and Long 1985). While there is evidence that increases in photosynthetic efficiency are usually accompanied by declining harvest intensity, so that crop yields stay roughly the same (Sinclair *et al*. 2004), we accept the arguments of Long *et al*. (2006) that the link has no fundamental physiological basis, and that it is possible to increase photosynthetic efficiency independently of harvest index.

Photosynthetic efficiency can be increased in multiple ways, but two prominent strategies are to replicate the photosynthetically efficient C_4 metabolic pathway in less-efficient C_3 plants, such as rice, and to select for variants of the photosynthetic enzyme Rubisco that bind more readily to carbon dioxide than to oxygen (Foulkes *et al*. 2009). Rubisco, particularly at high temperatures, somewhat perversely converts oxygen to carbon dioxide (photorespiration), thereby reversing the normal direction of photosynthesis.

Photorespiration plays an important metabolic role, and mutants that do not carry it out eventually die. However, there are organisms with varying degrees of specificity for carbon dioxide and oxygen, opening the possibility for more efficient photosynthesis (Long *et al*. 2006).

Considering the first of these strategies, the two photosynthetic pathways available to plants, the C_3 and C_4 pathways, are named for the number of carbons in an intermediate product in the two photosynthetic cycles (Klass 1998). The C_4 metabolism is more efficient than C_3 under any conditions, but the benefit is much less at low temperatures than at high temperatures; broadly speaking, plants in temperate areas tend to use the C_3 cycle, and those in tropical areas, the C_4 cycle (Long *et al*. 2006; Bowyer and Leegood 1997). Most plants with a C_4 metabolism also have a distinct anatomy – the Kranz anatomy – that concentrates carbon dioxide near to where Rubisco is located in the plant, thereby lowering the rate at which Rubisco converts oxygen back to carbon dioxide (Bowyer and Leegood 1997; Furbank and Taylor 1995; Long *et al*. 2006). Plants with a Kranz anatomy transport carbon dioxide into a region of the leaf where Rubisco is located, and prevent the carbon dioxide from migrating back out to the atmosphere after it has been transported. While it is possible that a small set of genes controls the Kranz anatomy, no such small set has been identified, and existing plans to reproduce the C_4 metabolism through genetic modifications aim at reproducing it in single cells. Without the Kranz anatomy, C_4 metabolism is not energetically efficient, as transported carbon dioxide molecules migrate readily out of the cells after they are released. For this reason, it is not clear whether this strategy, implanting the C_4 metabolism in C_3 plants using genetic engineering, will be successful (Long *et al*. 2006; Foulkes *et al*. 2009).

The other major strategy for increasing photosynthetic efficiency is to select for, or genetically engineer, plants that produce forms of Rubisco that preferentially bind to carbon dioxide rather than oxygen. There are many variants of Rubisco found in nature, and they do vary in their specificity for carbon dioxide relative to oxygen. There are some indications that the metabolic role of photorespiration is redundant with other possible mechanisms, and moreover that the currently dominant forms of Rubisco are not optimal for current atmospheric carbon dioxide concentrations. This raises the possibility that plants bred or engineered for increased Rubisco specificity might also yield better than current plants (Long *et al*. 2006).

Considering these and other strategies, Long *et al*. (2006) estimated the time required to genetically engineer plant material that could be incorporated into conventional breeding programmes. After introduction of the engineered material into breeding programmes, it can take about 10 more years before crops are ready for field testing. Long *et al*.'s mid-range estimates suggest that, with an active research programme, plant material with a 10 per cent increase in ε_u might be available within five years (although possibly less), while a 20 per cent increase might be achievable within 15 years. Adding 10 years for these gains to be expressed in field crops, it is possible – although challenging – for crops with 20 per cent higher photosynthetic efficiency to be in farmers' fields within 25 years.

THE YIELD GAP

Yields achieved by farmers are lower than the potential. For major cereal grains, realised yields range from 20 per cent to 80 per cent of potential (Lobell *et al*. 2009). There are at least three important reasons for yield gaps: less than ideal climate, water, or nutrients; losses due to pests and disease; and economic constraints, including poorly functioning credit markets, risk aversion, and an economic optimum that lies below the agronomic optimum, combined with modest economies of scale. We label these three factors "agro-ecological", φ_{AEZ}, "biotic", φ_{biot}, and "economic", φ_{econ},

$$y = \varphi_{\text{AEZ}}\varphi_{\text{biot}}\varphi_{\text{econ}}y_p. \qquad (3)$$

Mixed in with these changes are landscape-scale spatial variations, which will result in yields below potential. While landscape-scale variation can be reduced through management (Stevenson *et al*. 2001), and is therefore not purely determined by climate or soils, it is unlikely that it can ever be eradicated.

Agro-ecological constraints

Soils, climate, and slope may not be ideally suitable for a given crop, and so realised yields may be somewhat below yield potential, even if all other stresses – such as pests and diseases – are effectively controlled. Under the Agro-ecological Zone (AEZ) methodology as implemented by Fischer *et al*. (2002) in the Global Agro-ecological Assessment, land that achieves 90 per cent of the maximum is classified as "very suitable", land with 70 per cent of yield potential as "suitable", land reaching 50 per cent of potential as "moderately suitable", and 30 per cent as "marginally suitable".

In 2009, cropland (that is, that land defined as "arable" or under "permanent crops" by the FAO) covered an estimated 1.5 million hectares (Mha) (FAO 2011b). This is slightly larger than the estimated 1.4 Mha of land that is very suitable or suitable for cereals at intermediate levels of inputs, as assessed by Fischer *et al*. (2002); it is 25 per cent higher than the estimated 1.2 Mha of very suitable and suitable land that is not protected or under closed forest. This suggests that highly productive land is already occupied, and that any expansion will be onto less productive land.

Biotic stresses

The Green Revolution was made possible by a combination of several technologies. Synthetic nitrogen fertiliser and irrigation removed critical limits to crop productivity but resulted in excessively tall plants with heavy seed heads that fell over (or "lodged"). The breeding of dwarf plants solved this problem, while allowing more of the fixed carbon to be devoted to seeds rather than stems, but the short plants were vulnerable to shading by weeds; synthetic herbicides solved this problem, and, with pesticides to control pests and irrigation to supply a predictable amount of water, this completed the Green Revolution package (Evans 1998). Thus control of biotic stresses was central to the Green Revolution. Breeding programmes produced plants with improved resistance to specific diseases which, combined with improved pesticides, helped maintain high yields.

In addition to the Green Revolution strategies of breeding resistance and chemical control, genetic engineering could provide a route to increasing pest resistance (FAO 2004). There are also plenty of lessons from 10,000 years of practising agriculture; people have long exploited pest-plant interactions using strategies that now fall under the umbrella of integrated pest management (IPM) (Prokopy and Kogan 2009; Thomas 1999). IPM can have both economic and financial benefits (Cuyno *et al*. 2001), but the term covers a wide array of practices, and the benefits depend on the particular approach and the local situation.

In a survey of crop losses due to weeds, animal pests, pathogens, and viruses, Oerke (2006) estimates that wheat production was lower than its potential by between 14 and 40 per cent, and rice between 22 and 51 per cent, in different world regions, over the period 2001-2003. If a region with 40 per cent losses were to reduce its losses to 14 per cent, the yield gain would be 43 per cent, other things remaining the same; an improvement from 51 per cent losses to 22 per cent losses corresponds to a yield gain of 59 per cent. This suggests substantial potential yield gains by reducing losses.

Economic limits

There is a fundamental economic reason why realised yields will almost certainly lie below potential yield for a given technology, illustrated graphically in Figure 3. Because inputs cost something (money, time, environmental degradation, or social stress), and yields do not increase indefinitely with each marginal increase in inputs, eventually the yield benefit of an increase in inputs will be less than the additional cost of those inputs. To the extent that these costs are built into the farmer's assessment of profit, the level of inputs will almost always be less than the agronomic optimum (Lobell *et al*. 2009). Beyond this fundamental reason, poorly functioning credit markets (Rao 1989) and risk-aversion strategies (Antle and Crissman 1990) also contribute to yield gaps.

The gap between the economic and physical optimum level of inputs shown in Figure 3 can be reduced, if not completely closed, when there are economies of scale. As explained by Chavas (2008), small farms exhibit economies of scale, meaning that, among small farms of different sizes, larger farms are more profitable. But as farm size grows, these economies of scale are exhausted relatively quickly, so there is no additional gain from further expansion. This gives a characteristic "L" shape to how costs change with the size of farms. As Woodhouse (2010) points out, it is easy to confound farm type, farm size, and farm "scale" (meaning the relative amount of labour and capital). Different farm technologies are optimal for different sizes of farms; the L-shaped cost curve results from an "envelope" of curves for different technologies on different-sized farms (Chavas 2008).

The minimum observed gap between potential and realised yield seems to remain stubbornly around 20 per cent below potential (Lobell *et al*. 2009). It is likely to change only if there are significant inefficiencies, or if the relative price structure changes – that is, if crop prices rise faster or slower than the costs of producing the crop. Costs can increase because of changing prices for inputs such as fertiliser or pesticide. They can also change because external social or environmental costs are internalised by farmer and consumers, whether through market-oriented policies, such as taxes, cap-and-trade or similar schemes, or through personal choice. Evidence suggests that a mix of incentives and attitudinal changes would be required

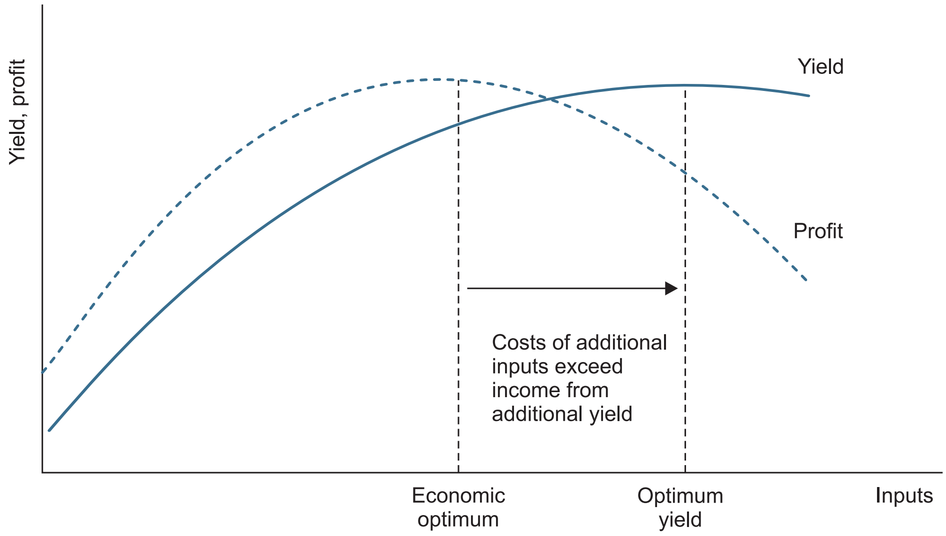

Figure 3: Economic limit to yields

to change farmers' use of inputs (Konyar and Howitt 2000); in particular, taxes alone are unlikely to be effective (Daberkow and Reichelderfer 1988; Falconer and Hodge 2000).

While there are economic models for farms, and estimates of how cropped area or yield responds to changes in prices, there is little evidence about the economic contribution to the yield gap. The available evidence suggests that this factor is comparatively resistant to change in both industrialised and developing countries. A study in the Philippines showed that farmers quickly learn to efficiently use new varieties and techniques (Antle and Crissman 1990). Angelsen *et al.* (1999), in a study in Tanzania, found almost no change in cropped land area with a change in fertiliser price. Models of aggregate agricultural production in Canada (Coyle 1993) and of farm households in Mexico (Taylor and Adelman 2003) suggest that farmers balance changes in land, labour, crop choice, and other factors with a change in inputs, while empirical work suggests that farmers substitute amongst chemical inputs, land, labour, and machinery (Daberkow and Reichelderfer 1988; Kislev and Peterson 1982), allowing them to buffer changes in prices.

There is also evidence that where constraints do exist, when those constraints are removed, the results can be dramatic. Huang and Rozelle (1996) argue that in the wake of agricultural reforms in China, technology adoption accounted for most of the yield gains – around 45 per cent between 1975 and 1990. Poorly functioning credit markets (Rao 1989) and insecure land tenure (Banerjee and Iyer 2005; Gebremedhin and Swinton 2003) also constrain farmers and reduce yields below the agronomic – and economic – optimum.

POTENTIAL SURPRISES

By using Equation (1) to estimate yields, this study is making a somewhat optimistic assumption that the only constraints on future yields come from the availability of good quality land, the rate of improvement in crops and cropping practices, and economic realities. However, there may be other limits to future agricultural production. We mention three potential limits that have been highlighted in the literature: threats to pollinators, risks of genetically engineered crops, and unsustainable use of phosphorus.

There is some concern that pollinators are disappearing (Biesmeijer *et al.* 2006) and may limit yields (Allen-Wardell *et al.* 1998), although the rates of disappearance and the seriousness of the threat is disputed (Steffan-Dewenter *et al.* 2005). Aizen *et al.* (2008) report that they find no pollination shortage, but they do see an increase in pollinator-dependent crops. Thus, although pollinators may not be critically limiting at present, they may become critically limiting in the future.

A major research agenda for agriculture will almost certainly include an important role for genetically engineered crops. Genetic engineering provides a promising avenue to reducing losses and increasing yields (The World Bank 2007; FAO 2004). While concrete gains have not matched early expectations (Sinclair *et al.* 2004), the same can be said of many promising new technologies, and the gains that have been achieved are significant. Nevertheless, genetically engineered crops pose risks that are not shared by traditionally bred crops (Rissler and Mellon 1996). Traditional breeding and genetic engineering both change the genetic makeup of crops, but breeding typically selects for traits that are unfavourable in wild plants – short stature, preference for seeds over storage for dry spells – while genetic engineering often breeds traits that are favourable in the wild – drought tolerance, pest resistance, photosynthetic efficiency. This means that traits from genetically engineered plants are more likely to spread beyond field boundaries. Also, if pest- or disease-resistant crops become widespread, they can foster the development of resistant diseases and pests. In the case of the Bt toxin, which is being engineered into many crops, this could endanger the use, for low-input farming, of naturally occurring Bt-producing bacteria (Rissler and Mellon 1996).

Phosphorus is an essential nutrient for both plants and animals. It plays a fundamental role in plant and animal metabolism – storing, transporting, and releasing energy. While phosphorus is relatively abundant, it also binds very strongly in some kinds of soils, reducing its availability for plants (Lægreid *et al*. 1999). Moreover, modern agriculture uses phosphorus in a mainly one-way stream that is not sustainable (Schröder *et al*. 2011; Sverdrup and Ragnarsdottir 2011). Phosphorous is required by all plants, and if it becomes scarce globally or regionally, it could severely impact crop production and human nutrition. With current practices, phosphorus should not become constraining during the 25-year horizon of our scenarios (Sverdrup and Ragnarsdottir 2011; Schröder *et al*. 2011). However, if conservation measures, such as those described by Cordell *et al*. (2011), are not adopted during the scenario period, then the significant increase in food and biofuel crop production that the scenarios imagine might not be sustainable in the long run.

None of these concerns may turn out to be long-term problems. However, there is reason to think that they could, and humanity's record for monitoring and responding to emerging threats is not encouraging. These surprises – or others we have not anticipated – could undermine any or all of the scenarios we have described.

5 SCENARIO QUANTIFICATION

Whether there will be sufficient land for food, feed, fuel, and fibre – and carbon sequestration in soils – depends on levels of consumption (van Vuuren *et al*. 2010; Wirsenius 2003), as well as the available biomass supply. The introduction presented four scenarios: Single Bottom Line, Meeting the Climate Challenge, Feeding the Planet, and Sustainability Transition. Each implies quite different levels of demands on biomass resources. Each also implies different levels of effort to improve the productivity and sustainability of biomass production for human use. In this section we develop quantitative assumptions that illustrate those differences.

To implement the quantitative scenarios, we created a model in the open-source scenario modelling software IPAT-S.[3] The schematic for the biomass model is shown in Figure 4; it is essentially an accounting model that tracks flows of carbon (as tonnes of carbon) and biomass (as tonnes of dry matter) through the economy. The purpose of the model is to estimate the land area needed to supply demands.

As we explain in more detail below, energy demands are adapted from the *World Energy Outlook 2011* (IEA 2010b), while food demands are adapted from the FAO study *World Agriculture Toward 2030/2050* (FAO 2006). In some cases we directly used the IEA and FAO scenarios, while in others we modified them to better fit the scenario narratives. We assume that chemical production tracks economic output (GDP), a choice that we justify later in this section. In the model we report values for 2008, 2020, and 2035, three of the years reported in the *World Energy Outlook*. The FAO food scenario does not report values for these years, so we used FAOSTAT data for 2008 and interpolated the reported scenario values for the other years.

DEMANDS FOR BIOMASS IN A LOW-CARBON ECONOMY

The categories near the top of Figure 4 – food, biodiesel, chemicals, ethanol, and energy from combustion – are final demands for products from the biomass production system. We discuss these demands, and some of the mediating factors between supply and demand, in this section.

Energy consumption and production

For energy, we adapted the IEA *World Energy Outlook*. Specifically, we used the following scenarios:

- **IEA New Policies Scenario:** This scenario assumes that existing policy commitments and plans for environmental protection or energy security are carried out, although in a cautious manner. This includes the commitments under the Copenhagen climate agreement and agreements to phase out fossil-fuel subsidies.

- **IEA 450 Scenario:** In this scenario, energy-related emissions follow a trajectory that keeps CO_2 concentrations below 450 parts per million (ppm) in the long run, but only after an initial overshoot. Thus this scenario fits our definition of a "low-carbon economy", but not very robustly, since it postpones aggressive action to reduce emissions, and implies substantial carbon sequestration after 2035.

- **Rapid Reduction Scenario:** We constructed the "rapid reduction" scenario by extrapolating trends in energy consumption and fuel shares from the IEA New Policies scenario to the IEA 450 scenario in such a way that cumulative emissions remain below 800 Gt CO_2 by 2035. Thus, unlike the IEA scenarios themselves, this is not a bottom-up assessment of low-carbon options. Instead, it is a simple extrapolation to generate a scenario consistent with keeping carbon dioxide concentrations below 450 ppm but with a lower chance of overshoot than IEA 450.

Underlying the IEA scenarios is an economic growth scenario. Global economic output grew at an average rate of 3.25 per cent over the 35-year period between 1971 and 2006. The rate has varied considerably between countries and regions, with high rates in the "emerging" economies, especially China, and low – even negative – rates of growth in Sub-Saharan Africa. The IEA *World Energy Outlook* assumes only a slightly slower average rate of growth between 2008 and 2035, 3.2 per cent (IEA 2010b), which, would slightly more than double the size of the economy by 2035.

3 IPAT-S can be downloaded from http://www.ipat-s.org/. The software is developed and maintained by the Stockholm Environment Institute for rapid quantitative scenario analysis. IPAT-S features a compact modelling language and fast execution times. Also, it supports mixed integer linear programming, but that feature was not used in this study.

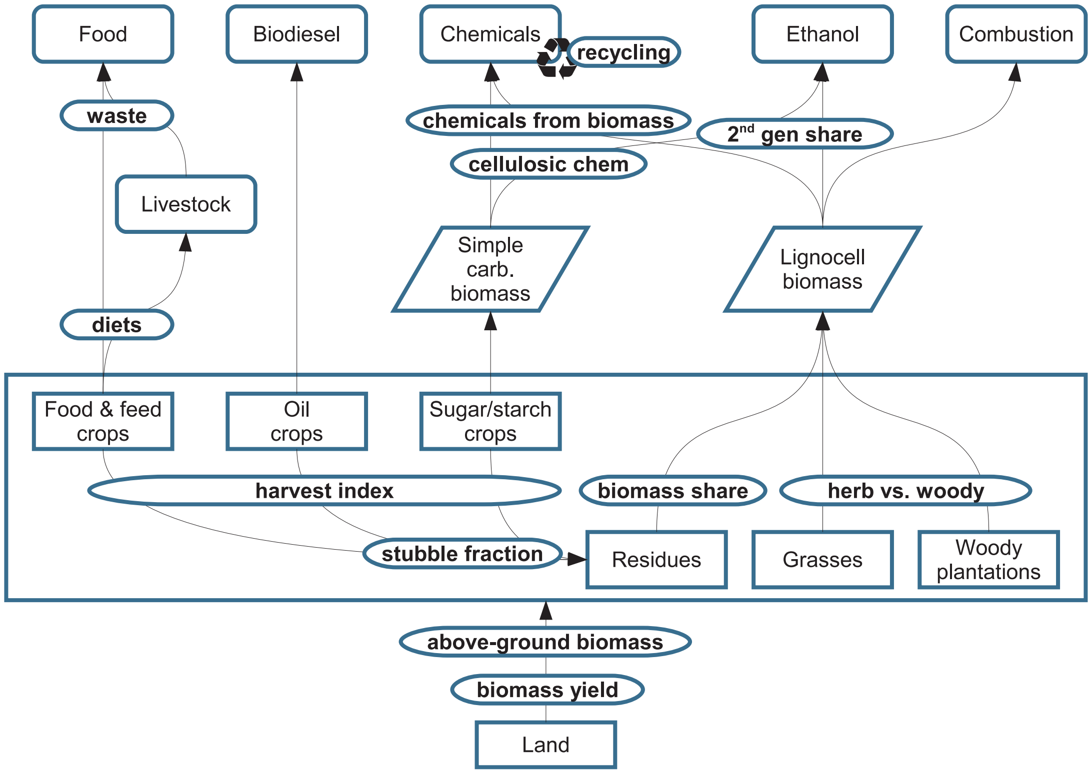

Figure 4: Scenario model schematic

One might question whether such robust growth could persist in a low-carbon economy. It is difficult to say. There will certainly be some costs, but it is not clear to what extent they will be sector-specific and to what extent economy-wide. Notably, the IEA assumes the same rate of economic growth in each of its scenarios – *Current Policies*, *New Policies*, and *450* – because of the substantial uncertainty surrounding the links between climate policies and economic performance.

Food consumption

For food consumption we adapted the FAO *World Agriculture Towards 2030/2050* scenarios. Specifically, we used the following two scenarios:

- **FAO World Agriculture Towards 2030/2050:** The FAO scenario describes a world in which rising incomes in developing countries translate into increased calorie consumption and increased consumption of animal products, although both of these grow at slower rates than in the past. These expected trends contribute to a significant reduction in undernourishment, although the rate of undernourishment continues to be high in many countries. However, the trends may not translate into better health for all, as higher consumption of sugars and fats increases risk of disease.

- **Smaller Footprint:** We introduce a scenario featuring reduced meat consumption and waste that is identical to the FAO scenario for total calories, but with 25 per cent less meat consumption in high-income countries by 2035 than in the FAO scenario by 2035, and 10 per cent less food waste in all countries.

The FAO has estimated that, at the start of the century, average apparent food consumption for the world was 2,789 kilocalories (kcal) per capita per day (FAO 2006). This average value, which includes food waste, exceeds physiological requirements (around 2,200 kcal per capita per day, according to Smil 2000). By 2030 the FAO expects this value to have risen to 3,040 kcal per capita per day, and by 2050 to 3,130 kcal per capita per day. The trend suggests a roughly 7 per cent rise in apparent food consumption per person over the 35 years between 2010 and 2045. Combined with population growth, this suggests a global increase of 42 per cent over the period; but it is possible to bring the increase below this level. In much of the world, food consumption is extremely low, and the increases are very welcome – they arise from a gradual improvement in living standards and should lead to improvements in general and maternal health, work capacity, and infant mortality. However, as much as one-third of the food that is produced is never consumed; it spoils or is discarded either before or after it reaches consumers (Foley *et al*. 2011).

People with relatively high incomes also eat large quantities of meat, whether in the general population in high-income countries, or at the high end of the income scale in low and middle-income countries. Animal products are certainly valuable in diets, providing dense protein and fat, while ruminant animals can convert biomass that is inedible to humans, such as grasses, into something that humans can eat, even as they help to recycle nutrients. However, in large quantities meat is unhealthy, and when livestock eat grain they inefficiently convert one potential food into another. Diets in high-income countries are demonstrably unhealthy (Smil 2000), and the adoption of healthier diets can reduce the environmental impact of food consumption (Tukker *et al*. 2011).

Thus, there is scope in a low-carbon world to reduce food demand while maintaining healthy and varied diets (van Vuuren *et al*. 2010). It is not necessary – or even necessarily desirable – that everyone should become a vegetarian (Wirsenius 2003), but there is considerable scope to alter the food consumption habits of high-income earners in a way that is positive both for them and for the environment.

Mediating factors between biomass supply and demand

In the scenario model, final demands for bio-based products are supplied by intermediate products, after taking recycling and waste into account. Food is supplied by food crops and livestock, while livestock are supplied by feed crops. Biodiesel is produced from oil crops. First-generation ethanol can be produced from simple, non-structural carbohydrates – sugar and starch – while second-generation ethanol can be produced from structural carbohydrates found bound to lignin – the ligno-cellulosic biomass in crop residues, grasses, and woody plants. (For more information about biomass constituents, see Annex 1.) Wood, grass, and residues can also be burned directly to produce heat for power generation, heating, and chemical processes.

Several assumptions determine the specific link between demands and land use, as indicated in Figure 4. The demand and process-related factors that vary by scenario are listed in Table 1.

- **Fraction of meat in diets:** Of total food calories, some fraction comes from meat and the rest from plants. Our baseline assumption comes from the FAO (2006), but in some scenarios we reduce the fraction of calories from meat in the high-income countries, as explained above.

- **Waste:** It is possible to reduce waste in both high- and low-income countries, but there are few estimates of the degree of savings that are technically and economically feasible. We assume no reduction in waste in Single Bottom Line and Meeting the Climate Challenge scenarios, and a 10 per cent reduction between 2008 and 2035 in the Feeding the Planet and Sustainability Transition scenarios.

- **Biofuels from biodiesel:** Of the total biofuel supply, at present about 25 per cent is from biodiesel (IEA 2010b). In the Single Bottom Line and Feeding the Planet scenarios we assume that this fraction stays the same through 2035. In the Meeting the Climate Challenge and Sustainability Transition scenarios, we assume that it drops to 10 per cent by 2035 as it is displaced by ethanol biofuel.

- **Chemicals from biomass:** Very few chemicals are now produced from biomass. In principle there is no reason why all chemicals could not be produced from biomass. We assume that these remain essentially zero in the Single Bottom Line scenario because of the continuing dominance of inexpensive fossil feedstocks. We also assume it remains zero in the Feeding the Planet scenario because it would otherwise compete with land for food. In the Meeting the Climate Challenge scenario, the emergence of a bio-based industrial sector and the cost-effectiveness of biorefineries pushes the share up to 20 per cent by 2035. A more aggressive effort to create a bio-based economy in the Sustainability Transition scenario leads to a 40 per cent share by 2035.

- **Second-generation share** and **cellulosic chemical share:** Of total chemical and biofuel production, some is from oilseeds, grains, or sugar, while the rest is from ligno-cellulosic biomass. This is given by the share of second-generation biofuels in total biofuel production and the share of cellulosic compounds in chemicals from biomass. The two factors are assigned the same value in the model. We assume that this factor reaches 10 per cent in the Single Bottom Line and Feeding the Planet scenarios, while focused research and economic incentives drive it to 20 per cent by 2035 in the Meeting the Climate Challenge and Sustainability Transition scenarios.

- **Chemical recycling:** Plastics and other carbon-based chemicals, whether from biomass or fossil sources, can be recycled, reducing the need for more feedstock. Plastic recycling rates in the United States were about 5 per cent around 2006 (Barnes *et al*. 2009) and ranged from around 5 per cent to close to 30 per cent in European countries (Hopewell *et al*. 2009). Allwood *et al*. (2010) estimated a current global average recycling rate of 5 per cent, with a 30 per cent maximum rate by 2050. We assume that the current rate doubles by 2035 in the Single Bottom Line and Feeding the Planet scenarios, reaches half the maximum rate in the Meeting the Climate Challenge scenario, and reaches the estimated maximum rate in the Sustainability Transition scenario.

The major demand assumptions that vary by scenario are shown in Table 1.

The IEA and FAO scenarios cover two of the most important potential demands for biomass resources. However, there are other demands that must also be considered: biomass as a chemical feedstock and biomass for ecosystem services.

Biomass as a chemical feedstock

Neither the IEA nor the FAO considered biomass as a feedstock to the chemical sector. We address it in this study because, while there is considerable scope to reduce energy consumption in the chemical sector (IEA 2010a), there is much less scope to reduce the carbon embodied in products, and demand for pulp and paper has continued to grow rapidly.

Biomass today is already used as an industrial product or feedstock. For example, a variety of biomass-derived fibres are used for clothing, ropes, rugs, and building materials (Vaca-Garcia 2008); oil and sugar crops are used as biofuel feedstocks (Agarwal 2007; Rosillo-Calle *et al*. 2000); and cellulose is used for paper and cellophane manufacture. In a low-carbon economy the outlook for chemical feedstocks is likely to change over time. The near future is likely to feature a rising demand for new materials, and the complex carbon compounds in biomass are good candidates for base materials.

In 2006, around 16 per cent of the total consumption of crude oil and petroleum products, and 11 per cent of natural gas consumption, was directed to non-energy uses, as reported by the IEA (see Table 2). Of this, the majority was as chemical feedstocks. A much smaller percentage – less than five per cent – of coal was directed to non-energy use, and very little of that was for chemical feedstocks. As shown in Table 2, a considerable amount of biomass (that is, the category "combustible renewables and waste" in the IEA energy statistics) was consumed for energy, an amount equivalent to 84 per cent of the total consumption of natural gas. Most of that consumption is traditional biomass use in inefficient stoves in developing countries.

Looking in more detail at petroleum in Figure 5, consumption for non-transport energy has been dropping as a share of the total since 1971. Transport fuel use has been increasing as a share, but so has consumption for chemical feedstocks. Considering consumption volumes, in Figure 6, as opposed to

Table 1: Major demand assumptions for scenarios

	Single Bottom Line	Meeting the Climate Challenge	Feeding the Planet	Sustainability Transition
Energy	IEA New Policies	IEA 450	IEA New Policies	Rapid reduction
Diets	AT 2050	AT 2050	Smaller footprint	Smaller footprint
2nd gen ethanol in 2035	10%	20%	10%	20%
Chemicals from biomass 2035	0%	20%	0%	40%
Plastics recycling rate 2035	10%	15%	10%	30%
Biofuels from biodiesel in 2035	25%	10%	25%	10%

Table 2: Fossil resources for energy and non-energy purposes in 2006

	Total final consumption (EJ)	Non-energy use (%)	Chemical feedstocks (% of non-energy)
Coal	29.2	4.3	7.0
Petroleum	145.8	16.5	61.9
Natural gas	51.6	10.9	98.1
Biomass	43.5	-	-

Source: International Energy Agency (2008)

shares, shows that non-transport energy consumption has been almost flat, despite global economic growth averaging 3.25 per cent per year between 1971 and 2006 (The World Bank 2010). Transport fuel demand has been growing at 2.25 per cent per year – somewhat slower than global economic output – while chemical feedstock use has been growing at 3.50 per cent per year – slightly faster than the rate of growth of the global economy.

The figures for fossil carbon consumption presented above suggest that today, its use as chemical feedstock is already noticeable – about 10 per cent of both petroleum and natural gas consumption. Also, it is growing, both in absolute terms and as a share of the total. These trends are likely to accelerate in a low-carbon economy (Brehmer *et al*. 2009).

The global carbon emissions envelope and ecosystem services

In order to provide the world with a good chance of staying within a safe climatic operating space, global greenhouse gas emissions must drop sharply (Rockström *et al*. 2009; Hansen *et al*. 2008; Meinshausen *et al*. 2009). Moreover, the need for economic development and poverty reduction in low-income countries suggests that high-income countries must not only sharply reduce their own emissions, but also provide financial support to poorer countries to support low-carbon development and prevent emission increases (Baer *et al*. 2008; Stanton 2011). Thus there is likely to be a substantial need for net carbon storage in soils and vegetation. Moreover, there is scope for carbon sequestration through changes in agricultural management practices (Smith *et al*. 2008; Lal 2008)

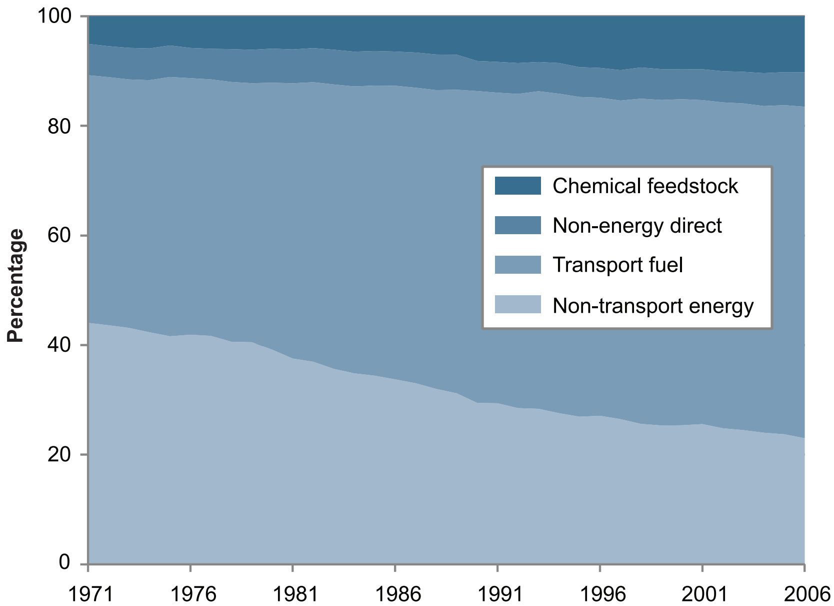

Figure 5: Global use of crude oil and petroleum products as shares of total

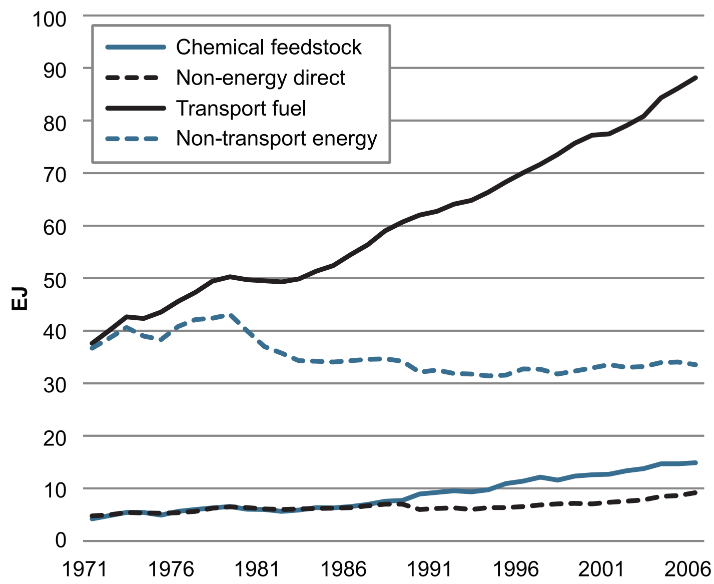

Figure 6: Trends in global consumption of crude oil and petroleum products

and forests. Furthermore, a sustainable agriculture must take care to protect valued ecosystems, even if these could be productive agricultural systems if they were fully exploited. We address carbon sequestration through the above-ground vs. below-ground partitioning of fixed carbon. We address ecosystem services indirectly through the agro-ecological and economic yield factors.

Summary

The special nature of biomass – that is, biologically-fixed carbon – means that it will be in high demand in a low-carbon economy. Biomass is essential for food, carbon storage, and ecosystem health, and both suitable and difficult to substitute as combustible material and as feedstock for the chemical and biofuel industries.

BIOMASS SUPPLY

The model schematic shown in Figure 4 has several factors related to biomass production. These are:

- **Biomass yield**, **above-ground biomass**, and **harvest index:** These are explained in detail in this section.
- **Stubble fraction:** Some part of the residues cannot be harvested cost-effectively. The fraction of the residues left standing is the stubble fraction. Hakala *et al*. (2010) set this factor at 30 per cent for cereals and oil crops, 25 per cent for maize, and 50 per cent for root crops. We used a factor of 30 per cent for all of our crop categories – food, oilcrops, ethanol crops, grass, and woody biomass.
- **Fraction of residues for biomass supply:** Of total residues produced from crops, some must be left on the ground and some might be used on-farm. We assume 10 per cent of total residue production is available as biomass feedstock for chemical or energy production.
- **Herbaceous vs. woody biomass:** In the model, ligno-cellulosic biomass demands are supplied from residues if possible. Any demands that cannot be met from residues are supplied either by grasses (herbaceous biomass) or tree crop plantations (woody biomass). This parameter, which determines the allocation between them, is set to 25 per cent woody biomass and 75 per cent herbaceous biomass in all scenarios.

The scenarios make different assumptions about the factors that influence yields. The potential to increase the various factors is listed in Table 3. As noted in the table, measures to improve yield potential may conflict with climate change mitigation or other sustainability goals. For example, in a meta-analysis of crop yield and nitrogen dynamics, Tonitto *et al*. (2006) found that legume-fertilised crops averaged 10 per cent lower yields than conventionally fertilised crops; at the same time, leaching was reduced by 40 per cent, which could significantly affect emissions of the potent greenhouse gas nitrous oxide. As noted in the table, partitioning of fixed carbon may need to shift away from above-

Table 3: Factors that contribute to yield in currently high-yielding (HY) and low-yielding (LY) areas

Factor	Symbol	Potential to increase: Potential	Potential to increase: Note	In a low-carbon economy	Under climate change	Under sustainable agriculture
Light interception	ε_i	HY: Low LY: Moderate	Already very high in HY; in LY, can breed improved canopy			
Light utilization	ε_u	+5-20%	Selection of Rubisco; C_4 pathway		Expected to change, but ambiguous	
Above-ground fraction	α	HY: Low LY: High	Already high in HY	Decrease: needed for soils		
Annual growing time devoted to crop	χ	HY: Low LY: High	There is potential for double and triple cropping	Possiby reduced: Legume-fertilized crops have less N leaching		Reduced: green manure, IPM, ecosystem maintenance
Biotic reduction	ϕ_{biot}	HY: Moderate LY: High	Considerable scope in many parts of the world			
Soil and climate reduction	ϕ_{AEZ}	HY: Low LY: Uncertain			Expected to change, but ambiguous	Decrease: reserve productive land for nature
Economic reduction	ϕ_{econ}	HY: Moderate LY: High		Depends on relative change in crop/fertilizer prices		Decrease as costs internalized
Harvest index	η	HY: Low LY: High	Already very high in HY	Ambiguous: needed for residue and soils		

ground to below-ground in order to add carbon to soils; the growing time in a particular location that is devoted to the crop may decline in favour of the ecosystems, the production of green manure, or integrated pest management strategies (Wojtkowski 2008); the economic reduction may become deeper as environmental and social costs are internalised, either implicitly in farmer decisions or explicitly through taxes, caps, or other market mechanisms; and the quality of agricultural land may decline if agriculturally productive land is reserved for nature.

Some trends are ambiguous. With climate change, the distribution of agro-ecological zones will also change. For a given precipitation and temperature, the area of suitable land can be estimated (Fischer *et al*. 2002), but there are large uncertainties in how these factors might change (Parry *et al*. 2007). Also, light utilisation depends on temperature and carbon dioxide concentration in a complex way, so that climate change may either increase or decrease efficiency. The harvest index may either increase or decrease in a low-carbon economy, depending on goals and strategies of farmers. Residues will be more important depending on how widespread second-generation biofuel and biochemical technologies become. Also, residues are important sources of animal feed and bedding, and changes in farming practice can enhance residue production and quality, generally at the expense of grains (Reddy *et al*. 2003). Moreover, residues contribute to soil carbon (Reilly and Fuglie 1998), which is expected to be a management goal on at least some farms in a low-carbon economy. Finally, farmer strategies will be affected in the future, as they are today, by relative changes in prices for crops (where an increasing price would increase the factor) and inputs (where an increasing price would reduce the factor).

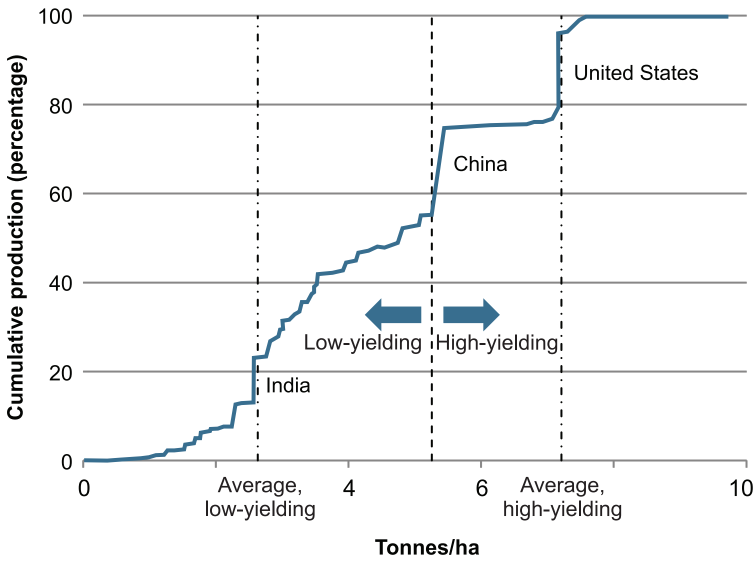

Figure 7: Cumulative cereal production in 2009 ranked from lowest to highest yields

Assigning numbers to the factors in Table 3 is challenging, partly because of the uncertainties and ambiguities listed above, but also because there is little information about the agronomic characteristics of crops in low-yielding developing countries. For this study we work at a highly aggregate level, assigning values for "high-yielding" and "low-yielding" regions. We show cumulative cereal production for the world in 2009 plotted against yield in Figure 7, using data from FAOSTAT (2010). In the figure, countries are sorted in order of average cereal yield, from lowest to highest. We define high-yielding countries as those contributing the upper 45 per cent of global production; that is, countries with the average yield of China or higher. With this definition, the average cereal yield in high-yielding countries in 2009 was 7.2 tonnes/ha and in low-yielding countries 2.6 tonnes/ha. Of global agricultural land, 25 per cent was in the high-yielding countries in 2009 under this definition. We next convert grain yields to above-ground biomass yields assuming a current harvest index of 0.55 in the high-yielding region and of 0.35 in the low-yielding region. Assuming that the above-ground biomass fraction is the same in both high-yielding and low-yielding regions, we estimate that total biomass yield in the high-yielding region is roughly 76 per cent higher than in the low-yielding region.

We present our quantitative assumptions in Table 4. For comparison to the increases shown in the table, between 1985 and 2005 yields increased by about 25 per cent (Foley *et al.* 2011). Were this same rate extended over a 25-year period, it would correspond to a 32 per cent increase.

To construct Table 4, we apply the factors separately to the high-yielding and low-yielding regions, and then aggregate the results assuming the same area shares as in 2009, although total agricultural area may change. That is, the high-yielding regions are assumed to have 25 per cent of the agricultural land and the low-yielding regions the other 75 per cent. We justify the assumptions in the rest of this section.

Light interception

Light interception ε_i depends on the orientation of leaves and the density of the canopy. The ideal canopy has flat (planophile) leaves when the plant starts to grow, later maturing into a canopy with planophile leaves at its base and vertical (erectophile) leaves at its top. Such an architecture provides maximum light interception. However, it is difficult to engineer such a canopy, especially in currently high-yielding plants, so there is little scope for increasing interception in the high-yielding region (Foulkes *et al*. 2009). In low-yielding regions there is probably some scope both for genetic improvements in the canopy architecture and changing agronomic practices. Using a model, Goudriaan (1988) estimated that the assimilated carbon for a plant with erectophile leaves in a dense canopy on a clear day in June was about 5 per cent higher than for a plant with planophile leaves under the same conditions. In the Feeding the Planet and Sustainability Transition scenario we assume, in high-yielding areas, that a combination of genetic and agronomic improvements leads to twice this increase in interception, or 10 per cent, between 2015 and 2035. In the other two scenarios we assume a 5 per cent increase over the scenario period.

Table 4: Contributions to yield in different scenarios, 2010-2035

	Single Bottom Line		Meeting the Climate Challenge		Feeding the Planet		Sustainability Transition	
Factor	**HY**	**LY**	**HY**	**LY**	**HY**	**LY**	**HY**	**LY**
ε_i	..	+5	..	+5	..	+10	..	+10
ε_u	+2	+2	+2	+2	+5	+5	+5	+5
α	..	+5	-5	+5	..	+10	-5	+5
χ	..	+5	..	+5		+5	-10	..
ϕ_{biot}	..	+10	..	+15	..	+25	..	+25
ϕ_{AEZ}	..	..	..	..	-7	-7	-7	-7
ϕ_{econ}	..	..	..	..	-5	+5	-5	+5
η	..	+10	..	+15	-5	+20	-5	+20
Above-ground biomass yield growth								
Total (%)	19		21		37		22	
Annual (%/yr)	0.71		0.77		1.26		0.81	
Crop yield growth								
Total (%)	23		27		43		28	
Annual (%/yr)	0.83		0.98		1.45		1.00	

Light utilisation

As discussed above, light utilisation ε_u for some crops could be improved by as much as 20 per cent over the next 25 years. However, this will not be true for all crops. Lacking more detailed information, we assume one-quarter of this increase, or 5 per cent, in the Feeding the Planet and Sustainability Transition scenarios. In the other two scenarios we assume that increasing light utilisation is not specifically targeted, but nevertheless increases modestly, by 2 per cent, as breeding programmes select for higher-yielding crops with better photosynthetic efficiency.

Above-ground biomass fraction

Estimates of the above-ground biomass fraction of crops α or, equivalently, the root-to-shoot ratio $R = 1/\alpha - 1$, are hard to find. We assume that in currently high-yielding areas there is no scope for improvement. For the low-yielding region we turn to Siddique *et al*. (1990), who measured root-to-shoot ratios of old and new wheat cultivars in a Mediterranean environment in Australia. At maturity, the corresponding above-ground biomass fraction of the newest cultivar was 25 per cent higher than the oldest cultivar. At best, this gives a rough indication of potential, because older cultivars have been replaced extensively throughout the world with modern varieties. In the Single Bottom Line scenario we assume that, because increasing agricultural productivity is not a primary policy or research focus, the above-ground biomass fraction does not change in the high-yielding regions and increases by only 5 per cent in low-yielding regions. In the Meeting the Climate Challenge and Sustainability Transition scenarios we assume that policies encourage greater soil carbon storage and discourage increased above-ground biomass. Accordingly, we assume that the above-ground biomass fraction declines by 5 per cent in the high-yielding region and increases by 5 per cent in the low-yielding region. In the Feeding the World scenario, a relatively low priority for carbon sequestration leads to a higher increase in above-ground biomass in low-yielding regions, of 10 per cent between 2008 and 2035.

Fraction of the year given over to the crop

The fraction of the year given over to the crop can be increased by shortening fallow times, or by planting a second (or even third) crop at the end or beginning of the growing season. These actions will also increase the cropping intensity, or the ratio of the area harvested to the area of cropland: an annual crop on a field that is left fallow every other year has a cropping intensity of one-half; a continuously cropped annual will have a cropping intensity of one; a double-crop, where two crops are grown on the same land over the course of a year, will have a cropping intensity of two; and a triple-crop will have a cropping intensity of three.

Data are available for cropping intensity, but not for the fraction of the year devoted to the crop, and the fact that the same factors increase both measures suggests that cropping intensity is a good proxy for the fraction of the year given over to the crop. However, they are not the same; the fraction of the year devoted to the crop cannot be larger than one, while the cropping intensity can. In general, an increase in cropping intensity overestimates the increase in the fraction of the year given over to the crop. With this caveat in mind, we use cropping intensity as a proxy measure.

Cropping intensity is very high in China, so the history of increased cropping intensity in China is interesting to study. Under mandated crop productivity improvements in China, cropping intensity increased by roughly 6 per cent between 1970 and 1978. However, under the market-oriented "household responsibility system", cropping intensity fell again, reaching levels in 1985 similar to those in 1983, but still 4 per cent higher than in 1970 (Lin 1992). Cropping intensity is higher in currently high-yielding areas than it is in low-yielding areas. Using data from FAOSTAT (2011a; 2011b), summing harvested area for annual crops, and dividing by total arable land for low and high-yielding countries shows that cropping intensity in high-yielding countries is about 11 per cent higher than in low-yielding countries. Part of the difference may be due to climate – increasing cropping intensity is mainly a tropical, rather than a temperate, strategy – but part is due to technique, technology, and crop choice.

In all scenarios except Sustainability Transition we assume that the fraction of the year given over to the crop increases by 5 per cent over the scenario period in currently low-yielding countries, and stays at its current level in currently high-yielding countries. This is roughly one-half the estimated gap in cropping intensity between the high and low-yielding countries.

In the Sustainability Transition scenario we assume that cropping intensity stays at its current level in low-yielding countries and declines by 10 per cent in high-yielding countries. While higher cropping intensities can help meet climate and soil nutrient goals – for example, increased cropping intensity under no-till systems has been found to increase soil carbon and nitrogen (Ortega *et al*. 2002; Sherrod *et al*. 2003) – we assume that the goal of maintaining and improving ecosystem health leads farmers to reduce this factor in high-yielding areas.

Biotic factors

If the regional gap between low and high losses for cereals due to pests and diseases were closed, it could result in a 50 per cent increase in the high-loss regions (Oerke 2006). We do not expect such a large improvement, because there will always be some gap between high and low-performing regions, even if the countries falling into those categories were to change. However, such a large gap suggests that the improvement could be substantial, with focused attention. Moreover, there is reason to think that low-impact methods could be as effective as chemical methods in controlling pests, diseases, and losses, although they may reduce yields through other factors.

With little to guide our assumptions other than the figures reported by Oerke, we set the improvement in the Feeding the World and Sustainability Transition scenarios to one-half the gap implied by Oerke's figures, or 25 per cent. In the Single Bottom Line scenario, there is little focused attention on agriculture, and so we expect a somewhat smaller improvement over the coming 25 years; we have assumed a 10 per cent increase. In the Meeting the Climate Challenge scenario we assume that there is some spill-over from improvements in the biofuel sector that leads to overall improvements of 15 per cent, somewhat higher than in the Single Bottom line scenario, but lower than in the other two scenarios.

Agro-ecological factors

We make the perhaps optimistic assumption in the Single Bottom Line and Meeting the Climate Challenge scenarios that there is no significant expansion into low-productivity agricultural land. Therefore, in these two scenarios we assume no change in this factor. In the other two scenarios we assume that productive agricultural land is reserved for or returned to nature in order to preserve and maintain ecosystems. The 7 per cent reduction corresponds to a shift from an average yield fraction of 0.75 (that is, predominantly "suitable" land with some "very suitable" and "moderately suitable" land) to 0.70.

Economic factors

As discussed in Section 3, the evidence for how far economic restraints on yields can be reduced is somewhat scattered. We assume no change in the contribution of economic factors to yield gaps in the Single Bottom Line scenario because there is little focused policy attention on agricultural production in this scenario. In the Meeting the Climate Challenge scenario, also, we assume no change in this factor, but for different reasons than in the Single Bottom line scenario: we assume that demand for biofuel crops increases revenue, but the need to reduce agricultural emissions results in higher prices – either explicitly, through market instruments, or implicitly, through consumer or farmer choice – for some inputs, with no net change. In the Feeding the Planet and Sustainability Transition scenarios, we assume that focused attention on low-yielding areas leads to improved credit markets, early-warning systems, and risk management. At the same time, in both high- and low-yielding areas, internalisation of external costs of inputs leads to larger yield gaps. The net effect is a decrease of 5 per cent in high-yielding countries and an increase of 5 per cent in low-yielding countries over the 25 years of the scenario.

Harvest index

Outside of the Green Revolution countries and regions there is considerable scope to increase harvest index. For low-yielding regions we assume increases of 10 and 15 per cent in the Single Bottom Line and Meeting the Climate Challenge scenarios, respectively. The faster increase in the Meeting the Climate Challenge scenario compared to the Single Bottom Line scenario is due to an assumed spill-over from breeding programmes for cash crops for biofuels in Africa and Asia, with no change in high-yielding areas. In the Feeding the Planet and Sustainability Transition scenarios, a focus on agriculture in developing countries leads to significantly higher increases in harvest index in currently low-yielding areas, while the need to reserve some residue for nutrients, cellulosic biomass, and livestock feed in low-impact livestock production systems leads to a decline in harvest index in currently high-yielding areas, and limits the increase in low-yielding areas. This translates into an increase of 20 per cent in the harvest index in low-yielding regions and a decline of 5 per cent in the high-yielding regions in each of these scenarios.

OUTPUTS FROM THE QUANTITATIVE SCENARIOS

Total annual emissions are shown in Figure 8, and cumulative emissions are shown in Figure 9, where historical emissions are taken from the Carbon Dioxide Information Analysis Center (CDIAC) (Boden *et al.* 2010).[4] As can be seen in Figure 9, cumulative emissions in the Meeting the Climate Challenge scenario have reached 1,000 Gt CO_2 by 2035. To keep cumulative emissions at that level by 2050, either annual emissions must drop to zero in 2036, or the world must achieve net negative emissions later in the century. In contrast, the Sustainability Transition scenario seeks to meet climate mitigation targets soon, with sharply reduced annual emissions by 2020 and slow growth in cumulative emissions.

Despite the strong reductions in emissions in the Sustainability Transition scenario, total demand for biomass is not much greater than in the Meeting the Climate Challenge scenario, as seen in Figure 10. A combination of low total energy consumption and lower meat consumption keeps total biomass requirements in check, despite a larger share of biomass in total energy supply (25 per cent in 2035, versus 13 per cent in the Meeting the Climate Challenge scenario). Food consumption dominates human use of biomass in all scenarios, but biomass use for both energy and chemicals increases.

Land for food and other biomass increases in all the scenarios except Feeding the Planet. All of the scenarios feature increasing yields, but the strong yield increases under Feeding the Planet, combined with low competing uses for biomass, allow agricultural land to shrink: see Figure 11.[5] While the increases in most of the scenarios may look modest on the graph, good agricultural land is already under pressure, and it will be difficult to increase the area in much of the world; only Africa has significant

4 The scenario calculation is a bottom-up calculation that does not – and is not expected to – exactly match the CDIAC figures. For the graphs we scaled the scenario values to match the historical trend from CDIAC.

5 Historical land area is from FAOSTAT. Our study does not include all the crops in the FAOSTAT database, and so the land area calculated by the model for 2008 is lower than the FAOSTAT value by about 200 million hectares. To construct Figure 11 we assumed that this additional area does not change, and we added it to the modelled values for each of the scenario years; that is, we adjusted the model values to match the historical data in 2008.

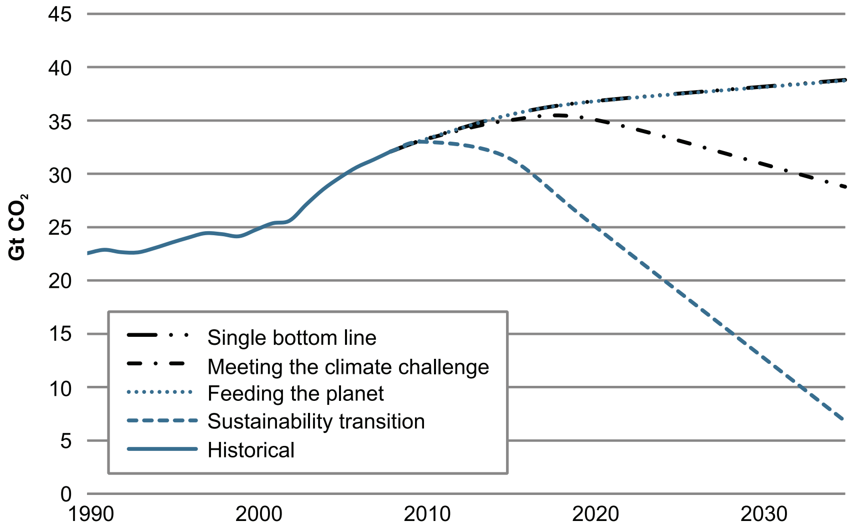

Figure 8: Annual emissions, historical and scenarios

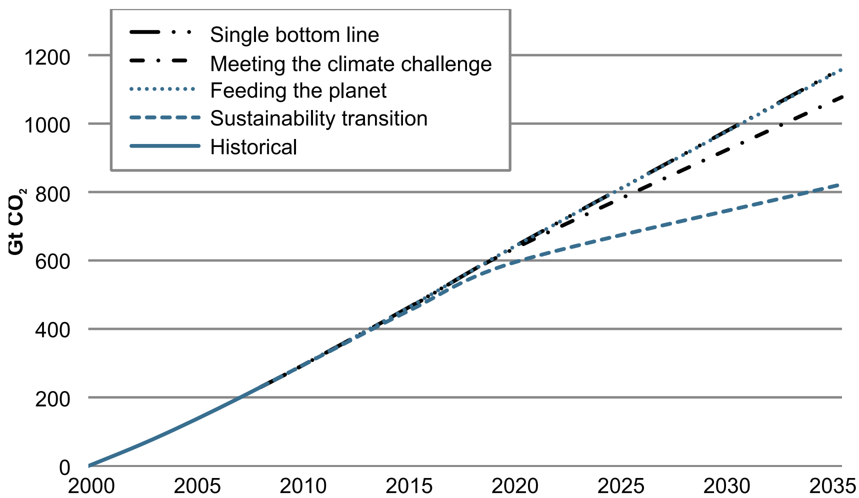

Figure 9: Cumulative emissions, historical and scenarios

areas of land that can be cultivated. Thus the increase in land use in most of the scenarios is significant and worrying.

Moreover, the Feeding the Planet scenario and the Sustainability Transition scenario both assume changing diets and the rapid development of a global effort to raise biomass and crop yields. This would be a substantial undertaking, but we are not alone in urging governments, foundations, research organisations, and private companies to pursue such an initiative (e.g., Foley *et al*. 2011). It could raise agricultural productivity in many of the world's poorest areas, but would require resources and sustained research attention over at least two decades.

The Sustainability Transition scenario combines the climate agenda with an agenda to feed the planet. It assumes the same focused attention on raising agricultural productivity, but also requires that some of the carbon fixed by the world's primary producers be used for fuels, chemicals, and carbon sequestration. And all of this while repairing damaged ecosystems and reserving carbon for nature. It is daunting, but possible.

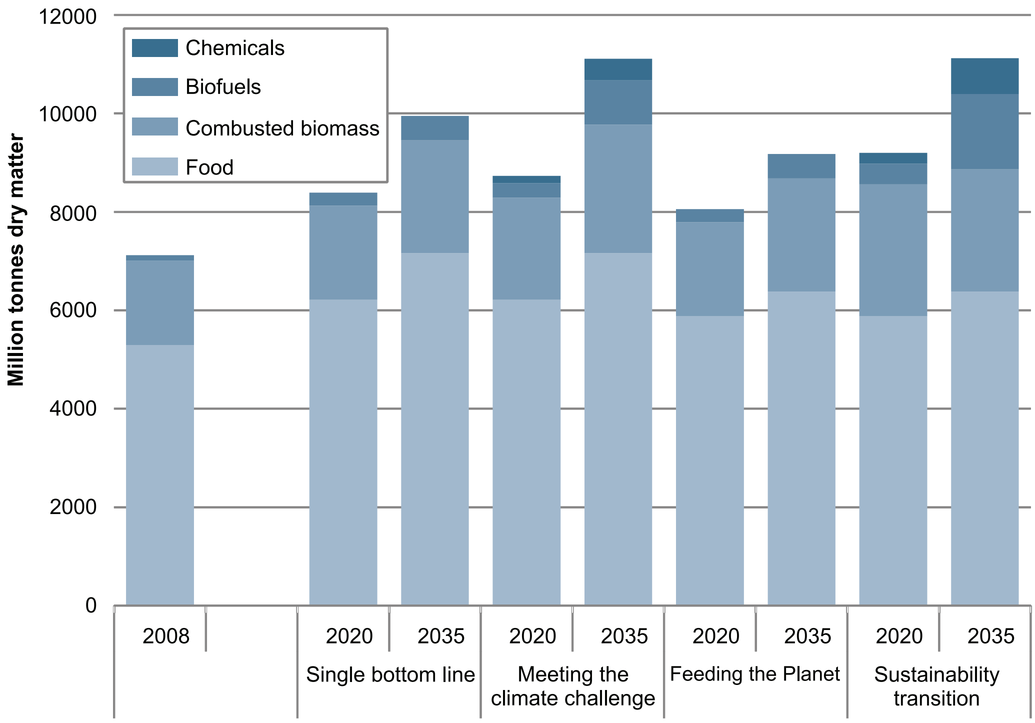

Figure 10: Use of biomass in the scenarios

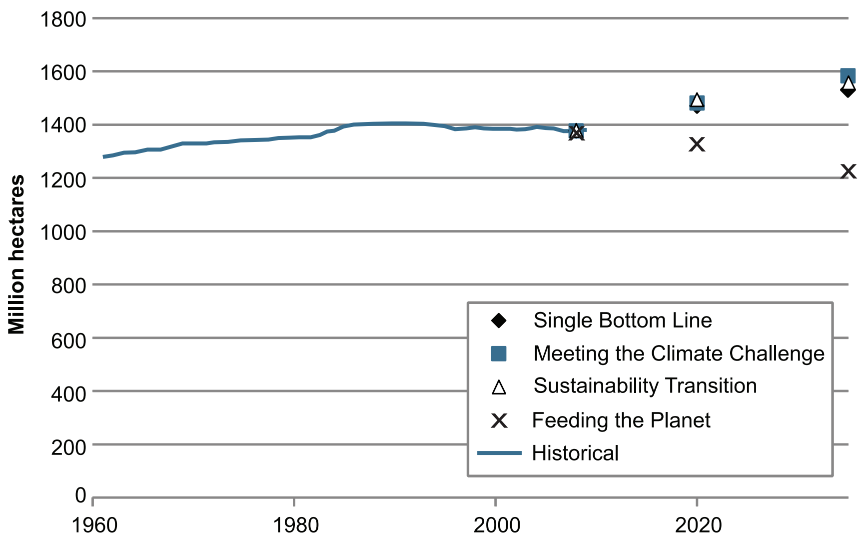

Figure 11: Land for food and biomass (traditional and non-traditional) in the scenarios

6 CONCLUSIONS

The 3C (Combat Climate Change) initiative seeks to mobilise business leaders, political leaders, and companies to meet the climate challenge. In this study, part of the partnership programme between 3C and the Stockholm Environment Institute, we explored the possibility for a low-carbon future that includes an emerging bio-based economy as a key component in a strong near-term mitigation strategy. Although this would place increasing pressure on an already stressed resource, we see great promise for biomass to help meet the urgent need to reduce carbon emissions. What is more, a bio-based economy, using known renewable resources, could underpin a long-term sustainable world. Even as we act to meet the climate challenge, we can anticipate the economy that might emerge from a low-carbon transition.

Both the size of the biomass resource and the structure of future demands are highly uncertain but essential for understanding the contours of a bio-based economy. This makes the problem particularly suitable for scenario analysis, which is best applied when there are high-impact, high-uncertainty factors influencing future trajectories. We constructed four scenarios, distinguished by the level of global policy attention on the climate and on agriculture. In the Single Bottom Line scenario only current climate policy commitments are pursued, and there is little focus on agriculture. In the scenario Meeting the Climate Challenge, the world embarks upon a meaningful programme to reduce carbon emissions, although it defers strong action until after 2035, and does not pay much attention to sustainable land use or agricultural productivity. In the Feeding the World scenario, anxiety over how to feed a growing population leads to a shift away from meat consumption, and a focused programme for increasing agricultural yields and reducing food waste. Finally, in the Sustainability Transition, strong attention is placed on both the climate and agriculture, with greater reductions in carbon emissions than in the Meeting the Climate Challenge scenario.

The results from the scenarios are summarised in Table 5. Considering agricultural footprint, the Single Bottom Line, Meeting the Climate Challenge, and Sustainability Transition scenarios all lead to a similar increase in land area. However, in the Sustainability Transition, part of the increase is because some productive agricultural land is given up to restore ecosystems, and some potential yield increases are sacrificed for a smaller environmental impact. At the same time, the Sustainability Transition helps meet the climate challenge through carbon sequestration and supplying feedstock for biofuels and combustible material for electricity and heat production. In contrast, the Feeding the Planet scenario only seeks to improve agricultural output while lessening agriculture's impact, which leads to a strong reduction in agricultural footprint. In the Meeting the Climate Challenge scenario, the world reduces carbon emissions but humanity's agricultural footprint increases through moderate increases in biofuels production and much more significant increases in food production with only modest increases in yields. The Single Bottom Line scenario, while perhaps most aligned with current political realities, may ultimately undermine itself; people can change the boundaries of what is politically realistic, but not the physical boundaries of the earth's safe operating space.

All of the scenarios shown in Table 5 have trade-offs. None of them reduces the footprints of both agriculture and carbon emissions. However, of them all, the Sustainability Transition is the most promising. It helps address the urgent climate problem, while at the same time it spurs improvements in agriculture that will bring multiple benefits, including food for our growing population and new agricultural products. Admittedly, the development of a bio-based economy faces coordination problems. While it is more efficient to produce more than one product from a single crop – the biorefinery approach – it is only profitable if there is a market for the products. This is not a problem if the products are conventional chemical feedstocks; otherwise it requires a chemical sector that uses biologically based feedstocks. Companies can close the gap by finding a niche within the value chain. The transition should therefore spur innovation – if we encourage the use of bio-materials, then entrepreneurs and businesses can take this on as a challenge, and thrive on it. And in the long run we will be building a solid and sustainable foundation for our future economy.

Whether anything like the Sustainability Transition scenario emerges in practice, the results from this report strongly suggest that the world needs a major, focused agricultural research programme involving both the public and private sectors. Returns on agricultural investment in both sectors are high, around 20-30 per cent, with a payoff period of

Table 5: Scenario outcomes for emissions and land use

	Reducing the Agricultural Footprint	Reducing the Carbon Footprint
Single Bottom Line	--	--
Meeting the Climate Challenge	--	+
Feeding the Planet	++	--
Sustainability Transi-tion	-	++

8-15 years in the private sector and 15-25 years in the public sector (Chavas 2008). The different payoff periods are consistent with a division of labour between public and private research, with public funding supporting long-term, fundamental research, and private funding translating the gains from that research into practical applications.

Part of the research programme should focus on the people who produce the crops. It is not always clear why yield gaps are as big as they are, and how small the gaps can become. Yield gaps do not have a simple source, and understanding how they can change requires better understanding of livelihoods and social and institutional dynamics in areas with persistently low yields. A research programme might also deliver on the promise of genetically modified crops targeted to the needs of farmers in poor countries, such as drought-tolerant crops. But genetic modification cannot be pursued at the expense of conventional breeding techniques (Foley *et al*. 2011). Progress on raising yields through molecular modification has been slow, and further research can learn from the few successes; these have mainly been long-term, multi-disciplinary research efforts that clearly identified the beneficial traits they were targeting (Sinclair *et al*. 2004).

The task that 3C has taken up is a large one, but one in which business has a clear and important role. Action to mitigate climate change is urgently needed now, but it will change the way that we live, work, and produce, and so will create new opportunities as the world shifts into a low-carbon way of living.

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ANNEX 1: CARBON POOLS IN PLANTS

Carbon fixed through photosynthesis is converted to sugars. The primary product is glucose, a sugar with a single functional unit (a monosaccharide) with a six-carbon ring (a hexose). Carbon is transported through plants mainly in the form of sucrose (a disaccharide) with two joined six-carbon rings (Strack 1997). From glucose and sucrose, a variety of plant materials are constructed. Following Poorter and Villar (1997), we classify them in this report as non-structural carbohydrates, structural carbohydrates, lignin, lipids, nitrogen-containing compounds, and all other compounds.

NON-STRUCTURAL CARBOHYDRATES

The non-structural carbohydrates include sugar and starch. All carbohydrates are composed of carbon, oxygen, and hydrogen, and contain high-energy bonds. Sugars are relatively small molecules that can be readily broken down to provide energy for chemical processes in the plant. Starches are composed of repeating sugar units (polysaccharides) that are used for long-term energy storage in plants. When the plant needs additional energy, it breaks starch down into sugars.

Non-structural carbohydrates make up around 20 per cent of the mass of dry matter in herbaceous (non-woody) plants, with more in the roots than in stems, and more in stems than in leaves. The amount is somewhat less in woody plants, which are between 10 and 15 per cent non-structural carbohydrate by mass. Plant seeds and the flesh around them can be very high in non-structural carbohydrates, with average values close to 60 per cent (Poorter and Villar 1997).

Aside from glucose, it takes energy to link sugar subunits together to build non-structural carbohydrates. If no energy were required, then the ratio of the mass of glucose required to build non-structural carbohydrates to the mass of the non-structural carbohydrate itself would be 1:1. On average, it is estimated that the ratio is in fact 1.09:1 (Poorter and Villar 1997).

STRUCTURAL CARBOHYDRATES

The structural carbohydrates are cellulose, a highly regular polysaccharide that forms tough fibres, and hemicellulose, a family of amorphous polysaccharides that bonds lignin to cellulose in cell walls. The cellulose molecule is an unbranched chain of glucose subunits (Turley 2008; Vaca-Garcia 2008). The subunits contain numerous oxygen-hydrogen pairs that permit extensive hydrogen bonding between adjacent cellulose chains. This linear structure with extensive lateral hydrogen bonds permits cellulose to form strong and durable fibres (Vaca-Garcia 2008). Hemicellulose consists of many different types of sugars. Because it is less regular than cellulose, it does not form fibres.

Structural carbohydrates typically make up between 20 and 30 per cent of the dry mass of herbaceous plants, although in some species it can be higher. In woody plants the contribution is much higher, close to 60 per cent in the stems or trunks of woody species. The energy required to build structural carbohydrates is higher than that of non-structural carbohydrates, with an estimated glucose-to-structural carbohydrate mass ratio of 1.22:1.00 (Poorter and Villar 1997).

The mass of all carbohydrates makes up around 40 to 50 per cent of the mass of herbaceous species and around 75 per cent of the mass of woody species. Sugars, and chains of sugars, are the most abundant chemical constituent of plants.

LIGNIN

Like carbohydrates, molecules in lignin are composed of carbon, oxygen, and hydrogen atoms. There is more than one lignin sub-molecule, each of which contributes to a highly-branched, cross-linked structure of complex constituents. Lignin is highly aromatic – that is, it is dominated by six-carbon rings that have alternating single and double bonds, as found in benzene (Strack 1997; Vaca-Garcia 2008). Lignin does not form hydrogen bonds, but it bonds chemically to hemicellulose, which then forms hydrogen bonds with cellulose (Vaca-Garcia 2008).

Lignin is a minor constituent in most herbaceous plants, making up about 2 to 4 per cent of the dry matter weight, although some herbaceous species have close to 20 per cent of lignin in their stems. It is a major constituent of woody plants, providing, on average, close to 10 per cent of the dry mass of leaves and around 25 per cent of the dry mass of trunks and stems. Compared to carbohydrates, it is costly for plants to synthesise lignin, consuming (in the most likely biochemical route) 2.12 grams of glucose for each gram of lignin produced, and emitting over four times as much carbon dioxide in the process (Poorter and Villar 1997).

LIPIDS

Lipids are fats and oils. Several plants have been bred to optimise their oil production, such as oil palm and canola (a low-acid cultivar of rapeseed). Lipids are used by plants both as a constituent of cell membranes and as an energy store for seed germination: during germination, lipids are converted to sugars to provide energy to the growing plant (Brownleader *et al*. 1997). Plant oils are used today for both food and non-food products and are the main feedstock for biodiesel (Harwood 1997; Turley 2008).

Except for seeds, lipids are a minor constituent in plants. Typically, they comprise about 5 per cent of leaf mass and lower percentages in stems and roots (Poorter and Villar 1997). However, plants bred for oil production produce copious quantities of seed high in oil, and in those plants lipid metabolism is significant. Lipids have the highest construction costs of all the molecular families found in plants, theoretically requiring 3.03 grams of glucose for each gram of lipid produced, and emitting 13 times the amount of carbon dioxide per gram as for structural carbohydrates.

NITROGEN-CONTAINING COMPOUNDS

The most important of the nitrogen-containing compounds in plants are the proteins. The enzymes that facilitate and direct plant functions are proteins, and they are important in food and feed. Biofuel production results in high-protein by-products and is then sold as animal feed (Turley 2008). They can also be used as nitrogen fertiliser.

The leaves of herbaceous plants can have quite high levels of protein, mainly the family of photosynthetic enzymes collectively called Rubisco. In herbaceous leaves, proteins average about 22 per cent of the total. Herbaceous stems and roots have smaller amounts, averaging about 10 per cent in each. The leaves of woody plants average just over 10 per cent of their mass as protein, while their trunks and stems are about 5 per cent protein or less. Seeds have comparatively high levels of protein, averaging a little over 20 per cent of their mass. Protein synthesis requires, in the most common but also most chemically expensive pathway, 2.48 grams of glucose per gram, and emits a similar amount of carbon dioxide per gram as does lipid synthesis (Poorter and Villar 1997).

OTHER

Other important chemical constituents include organic acids, soluble phenolics, and minerals. Each contributes at most around 10 per cent of the mass of leaves, and smaller percentages of other plant parts (Poorter and Villar 1997). Some of these compounds can be useful chemical feedstocks.

SEI - Africa
Institute of Resource Assessment
University of Dar es Salaam
P.O. Box 35097, Dar es Salaam
Tanzania
Tel: +255-(0)766079061

SEI - Asia
15th Floor Witthyakit Building
254 Chulalongkorn University
Chulalongkorn Soi 64
Phyathai Road Pathumwan
Bangkok 10330
Thailand
Tel: +(66) 22514415

SEI - Oxford
Suite 193
266 Banbury Road,
Oxford, OX2 7DL
UK
Tel: +44 1865 426316

SEI - Stockholm
Kräftriket 2B
106 91 Stockholm
Sweden
Tel: +46 8 674 7070

SEI - Tallinn
Lai 34, Box 160
EE -10502, Tallinn
Estonia
Tel: +372 6 276 100

SEI - U.S.
11 Curtis Avenue
Somerville, MA 02144
USA
Tel: +1 617 627-3786

SEI - York
University of York
Heslington
York YO10 5DD
UK
Tel: +44 1904 43 2897

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