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Review

Review: Assessing the climate mitigation potential of biomass

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Abstract: For many millennia, humans have used biomass for three broad purposes: food for humans and fodder for farm animals; energy; and materials. Food has always been exclusively produced from biomass, and in the year 1800, biomass still accounted for about 95% of all energy. Biomass has also been a major source of materials for construction, implements, clothing, bedding and other uses, but some researchers think that total human uses of biomass will soon reach limits of sustainability. It is thus important to select those biomass uses that will maximise global climate change benefits. With a 'food first' policy, it is increasingly recognised that projections of food needs are important for estimating future global bioenergy potential, and that non-food uses of biomass can be increased by both food crop yield improvements and dietary changes. However, few researchers have explicitly included future biomaterials production as a factor in bioenergy potential. Although biomaterials' share of the materials market has roughly halved over the past quarter-century, we show that per tonne of biomass, biomaterials will usually allow greater greenhouse gas reductions than directly using biomass for bioenergy. particularly since in many cases, biomaterials can be later burnt for energy after their useful life.

Keywords: bioenergy carbon capture and sequestration (BECCS); biofuels; biomaterials; food; energy return; climate mitigation

Abbreviation List

BECCS	bioenergy carbon capture and sequestration
CCS	carbon capture and sequestration
CO_2	carbon dioxide

CO_2-eq	carbon dioxide equivalent
EJ	exajoule = 10^{18} joule
EROEI	energy return on energy invested
FAO	Food and Agriculture Organisation
GHG	greenhouse gas
GJ	gigajoule = 10^{9} joule
Gt	gigatonne = 10^{9} tonne
HANPP	human appropriation of Net Primary Production
IPCC	Intergovernmental Panel on Climate Change
MJ	megajoule = 10^{6} joule
NPP	Net Primary Production
WEF	World Economic Forum

1. Introduction

Humans have long used biomass for three broad purposes: for growing food for humans and fodder for farm animals; for energy; and for materials used in construction, implements, clothing, bedding and other uses. Food has always been exclusively produced from biomass, although it is possible to produce carbohydrates artificially from hydrocarbons—and some food additives are today artificially produced. Further, diets vary greatly from country to country and over time. Traditionally, selection of both energy sources and materials was very simple: use the fuel or material that was cheapest and locally available.

For fuel, this nearly always meant biomass in some form or other: as late as 1800 with the industrial revolution well underway, global fossil fuel consumption was probably still under 10 million tonnes [1]. Even today, biomass is the preferred fuel in very poor households because of its low cost and local availability. In the form of fuel wood, as much as 50 EJ (EJ = exajoule = 10^{18} J) is consumed annually in low-income countries. Modern forms of bioenergy—liquid fuels such as ethanol, together with electricity and combined heat and power systems—only account for about 7 EJ [2]. Today, most of the world's primary energy consumption is still derived from fossil fuels—over 81% in 2014 [3].

International freight transport has made available a far wider range of fuels, particularly fossil and nuclear fuels, to most countries and regions. For example, over 64% of all petroleum used crossed national borders in 2015 [2]. However, such heavy reliance on imported fuels has now led to increasing concerns about energy security, so that an important argument made for the corn ethanol industry in the US is that it reduces dependence on oil from the Middle East. Supporters can also argue that it provides industry and employment in rural areas. A further justification for the ethanol program in the US is that it reduces air pollution emissions, a continuing concern in large urban areas. But in addition to availability, cost, energy security and regional employment considerations, two further considerations are vitally important: the challenges of global fossil fuel energy depletion and global climate change. A complication, of course, is that these various criteria can sometimes be in conflict with each other. Using food crops for bioenergy may well improve US rural prosperity and equity, but risk food security in food importing nations; food security is even more important than energy security.

Biomass-based materials have never experienced the total monopoly enjoyed by biomass-based food, or near-monopoly until 150–200 years ago for energy. Earth, stone and kiln-fired bricks and pottery have always had a major role as construction materials and food utensils, with small amounts of metals playing a minor role. These three broad uses for biomass are not mutually exclusive. Biomass construction materials can be also burnt for fuel after their useful lives. Similarly, spoiled food and used cooking oil can be used for energy, as can methane from sewage works, or from animal wastes.

The remainder of this review is organized as follows. Section 2 discusses human appropriation of Net Primary Production (HANPP), and concludes that if HANPP is raised much beyond about 45%, the absolute amount of NPP available to humanity will likely fall. This value thus sets an upper limit on all human uses of biomass. Section 3 looks at official projections of global food needs, and concludes that increasing quantities of both food and agricultural land will be needed to supply a growing world population. In Section 4, we show that although biomaterials are rapidly losing market share, they can usually enable substantial reductions in greenhouse gas (GHG) emissions if substituted for more energy-intensive materials such as steel or concrete. In Section 5, the role of bioenergy is then discussed. First, we discuss the energy return for biomass: only those bioenergy sources which give net energy can be considered part of global potential. Second, we review published estimates of its global potential, and stress their wide range. Section 6 discusses in turn the various possibilities for using biomass to maximise GHG emission reductions. Finally, Section 7 synthesises the findings of the earlier sections, and points to the need for a systems, "industrial ecology", approach to all human uses of biomass, in order to maximize its carbon reduction potential.

2. Human Appropriation of Net Primary Production

The maximum global limit for all human biomass use, whether for food, forage, energy, or materials, is ultimately fixed by the net primary production (NPP) of Earth's terrestrial ecosystems, defined as the gross annual fixation of living plant matter, minus respiration. Much of this annual production is already used by humans. Foley et al. [4] define this human appropriation of NPP (HANPP), as follows: "the share of global biological productivity that is used, managed, or coopted by human actions." The multiple uses of biomass, and the fact that HANPP is already a large—albeit contested—fraction of NPP (estimates vary from 0.10 to 0.55 [5], depending on what items are included), raises several questions which must be resolved if the global climate mitigation benefits of biomass are to be properly assessed. These questions include:

- How much can the overall HANPP fraction be increased before the absolute global total (in tonnes dry biomass) begins to fall?
- Can NPP itself be increased by humans?

Krausmann et al. [6] calculated that the HANPP, as a fraction of NPP, has doubled over the 20th century. Can humanity continue to increase its share of what Running [7] has found to be a roughly constant value of NPP of 53.6 billion tonnes per year in recent decades? However, according to Schramski et al. [8], terrestrial NPP has been reduced by 45% over the past two millennia, and in energy terms, is now about 2000 EJ. Kleidon [5] has argued that we cannot significantly raise HANPP. His estimate of present-day HANPP was 40%. Using a vegetation-climate system model, he found that when HANPP reached 45%, the absolute value of HANPP as measured by, for example, grams carbon/m^2/day, peaked and then fell for higher percentages of HANPP [9]. This peak occurred mainly because the simulated reduction in precipitation in many regions caused a fall in NPP in water-limited regions, and thus an overall fall in global terrestrial NPP.

Running [7] has likewise argued that total human use of biomass provides a "measurable planetary boundary for the biosphere". He estimated that current HANPP, which he put at roughly a third of NPP, can only rise to a maximum of around 47%. The 53% of NPP which he regarded as "non-harvestable" not only includes plant growth "critical for ecosystem services and biodiversity" but also plant roots, and "wilderness areas where no transportation exists for harvesting." In summary, both Kleidon and Running argue that HANPP can only increase by a small fraction before it runs into limits. Their two estimates for maximum HANPP are close: 45% and 47%, which correspond to 900 EJ and 940 EJ respectively (or roughly 50–52 Gt biomass assuming a lower heating value of 18 GJ/tonne [10]). These values are for *all* human uses of biomass, and thus represent upper limits on combined biomass use.

This conclusion is supported by the findings discussed above. The rise of human population from perhaps 200 million two millennia ago to 7.3 billion in 2016 has been accompanied by both large rises in HANPP (with a doubling over the past century [6]) together with a large fall in absolute NPP [8]. It is possible that humans could increase global NPP, but is unlikely, given the adverse effects of on-going climate change and pollution, water shortages in some regions, and possible limits on global phosphorus availability [11]. Overcoming these difficulties, if possible, would require large quantities of energy-intensive inputs, so that increased biomass production would be at the expense of lower net energy and lower GHG reductions.

Compared with other sources for energy or materials, it is very easy to "overshoot" on biomass use at all levels, local, regional and global. With wind energy, for example, a natural production limit occurs when the only sites left for accessible wind have low average wind speeds, so that the energy return on energy invested (EROEI) will be very low, and costs per kWh produced very high. In contrast, all dry biomass of a given type has similar calorific content (although for grasses it is lower than for woody biomass). But some biomass should not be used (e.g. some agricultural wastes) because it will lower soil carbon, or increase soil erosion. In such cases both agricultural production—and with it non-harvested residues—will fall. In terms of the above discussion, it is possible for HANPP to exceed its (sustainable) maximum value—at least for a while.

3. "Food First": Biomass for Agriculture

Many bioenergy researchers [12,13,14] explicitly employ a "food first" policy, meaning that the global requirements for food, both now and in the future, should be satisfied first before any bioenergy plantations are contemplated. There are good ethical reasons for explicitly safeguarding food supplies. Searchinger et al. [15] bluntly concluded that: "Our analysis of the three major models used to set government policies in the United States and Europe suggests that ethanol policies in effect are relying on decreases in food consumption to generate GHG savings." Hein and Leemans [11] have even claimed that using food-based crops is threatening future global food supplies by depleting the limited supplies of global phosphorus. However, while a "food first" policy could be considered an ethical imperative, this does not mean that either the existing nutritional mix, or medium-term trends as shown in the Food and Agriculture Organization (FAO) projections [16] in Table 1, should be seen as definitive.

The FAO project that world grain, milk and meat production will all rise from the 2011/13 period out to year 2023 (see Table 1). Grains for animal feed and for biofuels are expected to show higher growth than grain for food. The FAO also project continued strong growth for milk and meat production (Table 1) especially in developing countries. Elsewhere, the FAO have estimated that globally, 3009 million tonnes (Mt) of grain and 455 Mt of meat production will be needed by 2050, given continuation of present trends [17].

The land area for grain is only expected to increase marginally—most of the growth in production will result from anticipated higher yields (Table 1). Nevertheless, these yield gains are far smaller than those projected by Smeets et al. [12], gains which would greatly raise the non-food potential for biomass. Nevertheless, Burnley et al. [18] have argued that historically, “the net effect of higher yields has avoided emissions of up to 161 gigatons of carbon (GtC) (590 $GtCO_2$-e) since 1961.”

Table 1. FAO annual global production of various commodities, years 2011/13 and 2023.

Food commodity	2011/13[1]	2023[1]	% increase
Grains (Mt)	2391	2753	15.2
Animal feed	*819*	*976*	*19.2*
Biofuels	*145*	*183*	*25.5*
Food & other	*1427*	*1594*	*11.7*
Grain area (Mha)	716	736	2.8
Yield (t/ha)	3.34	3.74	12.0
Milk (Mt)	749	928	24.0
Meat (kg/capita)	33.8	36.2	7.1

[1] crop years. Source: [16].

Different foodstuffs vary greatly in their food energy return per unit of energy invested (and consequently in their CO_2-equivalent (CO_2-eq) cost per kilojoule of food energy), and also in the land required per kilojoule of food energy. Acker et al. [19] have shown that in Arizona, USA, the energy inputs can often be more than 100 times the energy value of the foodstuffs grown, although many foods, like lettuce, are not eaten for their energy food value. But even for potatoes, where food energy is important, the ratio was still over 29. Over half the energy input for all foods combined was for irrigation and chemicals (fertilizers, pesticides). Such energy analyses illustrate two important points about net energy for foodstuffs. First, that food production is an energy sink, which we tolerate because we can’t do without food—there are no substitutes. Second, the energy return (and corresponding carbon emissions) vary greatly between foodstuffs, being especially high for meat and dairy products [20].

Several researchers have examined the effect that the world population moving to a more vegetarian diet would have on the availability of bioenergy [13,21,22]. In effect, while still giving priority to food production, this approach seeks to improve the efficiency of food provision. There are thus two approaches to reducing the land needed for food agriculture: agricultural intensification and dietary change, although the energy and climate change implications of these two approaches are very different. Intensification implies a non-linear increase in inputs of energy-intensive irrigation, fertilizers and pesticides, and N_2O emissions [23,24,25], whereas with dietary change, land and inputs would be reduced roughly in proportion to reduced total output.

4. Biomass for Materials

We have shown that even with a "food first" policy, there is still some scope for reducing food's "ecological footprint" by dietary shifts. As we discuss below, natural, biomass-based fibres compete with synthetics, and a variety of non-biomass construction and packaging materials compete with biomass-based ones. (Curiously, although a vast amount has been written on the interaction between food production and bioenergy, few papers have dealt in a systematic way with the similar tradeoffs between bioenergy and biomaterials, but see, for example, [26,27,28]). Given this capacity for substitution, materials selection should be guided by criteria other than monetary cost, including energy and CO_2-eq minimisation for a given application, such as a new building. This section looks at the general effects of possible increases in biomaterials use on bioenergy potential.

Carmichael [29] has reported that synthetic fibre production in 2014 was 55.2 million tonnes, more than double natural fibres like wool and cotton at 25.6 million tonnes. Overall global plastics production, of which artificial fibres are a sub-set, was 311 million tonnes in 2014 [30]. The steady growth of plastics for consumer products, construction and packaging materials, and synthetic fibres, suggests the possibilities for substitution between biomass-based materials and plastics, largely made from fossil fuels. The World Economic Forum [30] has even promoted the manufacture of plastics from wood products, instead of from fossil fuels.

Table 2 shows the growth in global production of materials—kiln-fired bricks, steel, cement, aluminium and plastics—which compete with wood or wood products in areas such as construction, packaging and textiles. As can be seen, competitor materials have all roughly doubled or even tripled in production over the period 1990–2014, whereas non-fuel wood production has barely grown. Concrete (where sand and crushed rock aggregate together typically have a mass 5–6 times the cement component) today dominates construction materials by mass. Clearly, wood is losing market share in the construction materials sector, just as bioenergy has lost a small share of the energy sector. Yet it has been argued [31,32] that increasing use of timber products can reduce overall GHG emissions (and energy use) in construction, because of the carbon intensity of alternative products. For European conditions, Bribián et al. [32] have calculated the emission factors for sawn softwood used in construction and various other construction materials, shown in Table 3. Intensity has been expressed on both a mass and volume basis.

Table 2. Annual global production of various materials (Mt) 1990, 2000 and 2014.

Year	1990	2000	2014
Wood (non-fuel uses)	1700	1620	1836
Kiln-fired bricks	NA	NA	5250[a]
Cement	1227	1590	4180
Steel	770	849	1670
Plastics	106	160	311
Aluminium	20	25	49

a: 2013 figure, and assumes 3.5 kg per brick. Sources [30,33–37]

Table 3. CO_2-eq intensity of various construction materials.

Material	kg CO_2-eq/kg	kg CO_2-eq/m^3
Sawn softwood	0.30	180
Concrete	0.14	325
Reinforced concrete	0.18	455
Steel (reinforcing)	1.53	12,055
Aluminium	8.57	23,140
Plastics (PVC)	4.27	5975

Source: [32]

Gustavsson and Sathre [31] have highlighted the numerous difficulties in attempting to evaluate whether substituting wood products for other materials results in net CO_2-eq emission savings. The main one is that comparisons cannot be made on a simple material mass basis (as in the building materials emission factors given above), since the cladding for a timber house, for example, will have a far lower mass than for a brick one. Another problem is the estimation of carbon storage duration for biomass products, which will be very different for heavy construction timber compared with packaging. Gustavsson and Joelsson [38] analysed the production energy costs of a number of comparable residential buildings in Sweden. Of interest here is the energy comparison of two four-storey residential buildings, one concrete-framed, the other wood-framed. Overall, the wood-framed building required 2.33 GJ/m^2 of floor area primary energy, compared with 2.79 GJ/m^2 for the concrete framed one, even though the frame constituted only a minor share of total production energy costs.

Timber can also reduce carbon emissions. In an earlier analysis, Gustavsson et al. [39] calculated net carbon emissions for two "functionally equivalent" buildings, one timber-, one concrete-framed. In their carbon accounting they included: "emissions due to fossil fuel use in the production of building materials; the replacement of fossil fuels by biomass residues from logging, wood processing, construction and demolition; carbon stock changes in forests and buildings; and cement process reactions." They showed that wood framing resulted in net reductions of 30 - 130 kg C per m^2 of floor area, the exact value depending, among other factors, on the fuel used for electricity production. Importantly, they concluded that: "The carbon mitigation efficiency, expressed in terms of biomass used per unit of reduced carbon emission, is considerably better if the wood is used to replace concrete building material than if the wood is used directly as biofuel." Wood's superiority in energy costs suggests that it will also reduce carbon emissions under a range of electricity feedstocks.

What if wood had kept its 1990 market share for materials? In 1990, wood accounted for 44.5% of the mass of materials listed in Table 3 (bricks were excluded, since no 1990 figure was available). By, 2014, the proportion had fallen to 22.8%, about half its 1990 value. If wood had merely maintained its 1990 share, an extra 1900 Mt of wood would have been used—if available. This rough calculation shows its importance: at a lower heating value of around 18 GJ per tonne (GJ = gigajoules = 10^9 joules) [10], 1900 Mt corresponds to about 34.2 EJ of primary energy—greater than lower-end estimates of global bioenergy potential. Further, if wood's share in the decades before 1990 was used instead as the basis for calculation, the energy value would be much higher than 34.2

EJ. Already, a wood construction revival is underway, an example being an 18-storey dormitory block under construction in Vancouver [40].

So how to decide between bio-materials and bioenergy? We address this question after looking at the published literature on bioenergy potential.

5. Biomass for Energy

Bioenergy is very different from other renewable energy (RE) sources in that it is the only RE that relies on combustion to release its (chemical) energy, which makes it similar to fossil fuels. It can thus be co-fired with coal in thermal power stations. Also, like fossil fuels, it can be stored and used later, overcoming the intermittency problems facing its main future RE competitors, solar and wind energy. Because of these advantages, many researchers have placed great hopes in bioenergy to both replace fossil fuels and to play a major role in mitigating climate change [12,41,42]. The Intergovernmental Panel on Climate Change (IPCC) in their latest report [43], likewise envisaged such a role for biomass. Nevertheless, IEA statistics [3] show that although all energy supplied globally from “biofuels and waste supplies” more than doubled from 27 EJ in 1973 to 59 EJ in 2014, its share of global primary energy fell slightly from 10.5% to 10.3% over the same period.

5.1. Energy Return on Energy Invested for Bioenergy

An obvious selection criterion for all energy sources, which has always been implicit, is that an energy source has to deliver *net energy*: the energy output has to be greater than the energy inputs needed to produce that energy and deliver it to the point of use. That is, the EROEI must at least exceed unity, and ideally should be much greater [44]. The relevant inputs for bioenergy plantations would include the energy costs of seed development, land preparation, planting, fertilizers and herbicides, irrigation and farm equipment for growing the biomass. Harvesting, bioenergy transport, drying and processing of the crop all entail additional energy inputs. It is not clear what fraction of the technical bioenergy potential estimates discussed in Section 5.2 would pass this net energy test. It is also possible that some bioenergy sources could deliver net energy, but fail the second hurdle: the need to deliver GHG reductions.

The only exceptions to the need for positive net energy are for new energy sources. Possible novel sources of electricity, like fusion energy, or new types of PV cell, can afford to be an energy sink while under development, in the hope that future technology developments will lower the input energy requirements and allow the energy source to produce net energy. Also, if the energy is upgraded to a more useful form, such as with converting biomass to electricity, output energy can be less than input energy. For food and biomaterials, matters are more complex. As we have shown, food production is an energy sink, although the energy subsidy per kilojoule of food varies greatly from crop to crop. Similarly, materials are not produced for energy, so an EROEI value is not relevant; nevertheless, it is still important to try to minimize their energy inputs and resultant GHG emissions. But unlike food, many biomaterials can be substituted for competing, more-GHG intensive materials, as discussed in Section 4.

Early analyses of energy return for biomass crops often produced high estimates, although with considerable variation. In two studies of short rotation tree crops in northern Europe, EROEI values of 14.4 and 64.8 were calculated, even when yields were similar. The higher value study, however, excluded both fertilizer and harvesting/chipping costs from energy inputs. In neither case was irrigation required, which can have high energy costs [10]. Gasol et al. [45] found even higher EROEI values—an EROEI value of 88 for direct energy stored in the biomass—for energy crops (*Brassica carinata*) grown in Spain. However, the calculations were for experimental plots only. In a more recent study, Murphy et al. [46] examined the energy return for *Miscanthus* grown in Ireland. They calculated far lower EROEI values, ranging from 3.6 to 6.5, with different fertilizers and different fertilizer transport distances (50 or 100 km) accounting for the variation.

Bioenergy can also be upgraded and used for liquid fuels, but reported EROEI values are low. De Castro et al. [47] examined the EROEI for liquid fuels made from food crops. For bioethanol, the values were 1.25 for US corn ethanol, 5.0 for Brazilian sugar cane ethanol, and for biodiesel, 1.5-3.0. Wang et al. [48], reported comparable values of 1.61 for corn and 4.32 for sugar cane ethanol, but higher values (up to 6.01) for cellulosic ethanol.

The variation in EROEI values reported here is to be expected, given the different bioenergy crops examined, and the fact that different areas will have varying soil fertility and rainfall. But in general, lower EROEI values are more likely, for two reasons. First, even analyses based on field crops often omit necessary energy inputs. Second, analyses often implicitly ignore the "food first" approach, using results from premium agricultural soils.

5.2. Estimates for Global Bioenergy Potential

Assessing the global technical potential for bioenergy is difficult and ambiguous, as the research discussed in this section will show. But it is also important, since we need to know in general whether bioenergy can be a major future energy source, or merely a marginal one. Further, if bioenergy potential is small, it can never be more than a minor climate mitigation solution, even if GHG reductions per EJ of fossil fuel energy replaced were large. But while technical potential estimates increasingly take into detailed account future food needs, the question of biomass-based materials is largely ignored. Implicitly, despite some discussion in the literature on increasing biomaterials use, not much change from present trends is presumably expected. Further, the need for an adequate energy surplus, as discussed in Section 5.1, is also often ignored.

Global bioenergy potential consists of two very different parts. First, energy can be produced from dedicated plantations of fast-growing trees such as willows, eucalypts and poplars; from perennial grasses such as switchgrass and Miscanthus [49]; or from conventional food crops such as cereals, sugar cane and oil seeds. Second, wastes from agriculture and forestry, food wastes, municipal garbage, etc. can also be used for fuel. Over the past two decades, many estimates for the technical potential (both national and global) from both energy crops and wastes have been published, a selection of which are discussed here.

Smeets et al. [12] published in 2007 a detailed review of global potential from dedicated crops using a bottom-up approach. They calculated a global potential of 215–1272 EJ per year. The key variable that would enable bioenergy to play a major role by year 2050 was improvement in agricultural productivity, since the authors assumed that only land surplus to agricultural needs could be used for bioenergy crop production. An additional 150–170 EJ was assumed to be available annually from forest growth or forestry and agricultural residues, for a total of 365–1442 EJ. Earlier research had calculated an even higher potential, 1546 EJ per year [50]. These figures of 1442 and 1546 EJ suggest that bioenergy alone could satisfy human primary energy needs for the foreseeable future. However, they are well in excess of the 900-940 upper limit derived for *all* biomass from HANPP considerations (see Section 2), and are thus clearly far too optimistic.

On the other hand, some researchers have seen a much reduced role for biomass [50–57], with values as low as 27 EJ or less. Searle and Malins [50], also for the year 2050, estimated that "the maximum limit to long-term total biomass availability is 60–120 EJ yr^{-1} in primary energy". Most of this potential would come from bioenergy plantations, with only about 20 EJ from various waste sources. Smith et al. [51] similarly looked at the maximum potential contribution that bioenergy could realistically make to year 2050 energy needs, and found a range from about 60 to 180 EJ, or 5% to 15% of all year 2050 estimated primary energy use. For Canadell and Schulze [58], bioenergy could deliver between 26 and 64 EJ per year of primary energy by 2050. Creutzig and colleagues [49] concluded that bioenergy could annually supply 10–245 EJ primary energy by 2050. While 245 EJ represents almost half of 2014 global primary energy use [3], 10 EJ is a trivial share.

The reasons given for this spread in potential are varied. Johnston et al. [52] mainly stressed that bioenergy crop yields (in tonnes per hectare) have been over-estimated, in many cases by 100% or more. Searle and Malins [54] have reached similar conclusions, because of such factors as crop losses and "edge effects in small plots" over-estimating real world harvests. For others, it is the need to preserve biological diversity [15,44] and crucial ecosystem services [50], or the lack of suitable land for energy crops [51]. For Davis et al. [57] who approach the question of bioenergy potential from an ecologically-informed viewpoint, global estimates become systematically smaller as needed limiting factors are progressively applied.

Others have cast doubt on the efficacy of using crop residues and forest wastes. Karlen et al. [59] argued that their use is simply another case of "attempting to solve one environmental problem by inadvertedly creating another." They stress the multiple ecosystem services that crop residues provide: "filtering and storing water; decomposing chemical residues and toxicants; carbon capture and sequestration/storage (CCS) and the same for nitrogen (N); providing wildlife habitat; mitigating flooding; soil, water, and air quality; food, feed, fiber, and energy production; and community development."

This optimal fraction of waste residues to remove from agricultural fields and forests has an analogy in the optimal fraction for HANPP, discussed earlier. Past a certain removal fraction of residue, extra fertilizer will need to be added to the fields to replace the nutrients removed, with an attendant increase in both this energy-intensive input and emissions of N_2O [25]. Soil losses from wind and water erosion would also rise, depending on local factors such as terrain slope, local meteorology and soil type, lowering yields and hence residues available for bioenergy.

In summary, the question: "What is the global potential for bioenergy?" has no definitive answer. Hoogwijk et al. [28] have given a list of reasons for why this is the case: "Crucial factors determining biomass availability for energy are: (1) The future demand for food, determined by the population growth and the future diet; (2) The type of food production systems that can be adopted world-wide over the next 50 years; (3) Productivity of forest and energy crops; (4) The (increased) use of bio-materials; (5) Availability of degraded land; (6) Competing land use types, e.g. surplus agricultural land used for reforestation."

6. Climate Change Mitigation Potential for Biomass

The requirement for positive net energy return in the case of bioenergy is today increasingly joined by a new one—the need for climate change mitigation. This requirement is the motivation behind the European Union (EU) directive that member states should obtain 20% of their energy from renewable energy (RE) sources by 2020 [60].

For simplicity, many analyses of RE only consider CO_2 emissions for comparison with fossil fuels. This makes sense for fossil fuels combustion, since emissions of other GHGs usually add only a few percent to CO_2-eq emissions. (However, for natural gas, the advantage of relatively low CO_2 from combustion may be considerably offset by gas leakage from pipes [61], by high CO_2 content of some gas fields—as high as 70% in the Natuna gas field in Indonesia [62]—and from tight gas released by hydraulic fracturing). For wind energy and solar energy, nearly all GHG emissions arise from the CO_2 from input fossil fuels, together with a small contribution from site clearance. For some other RE sources, emissions of non-CO_2 GHGs can be very important. Hydro dams in the tropics with reservoirs that flood forests can have high emissions of both CH_4 and CO_2 as the vegetation decays [63]. Geothermal energy can also directly emit small amounts of both CH_4 and CO_2, although for both hydro and geothermal, background emissions of these gases should be established to assess their true climate change effect. For biomass, it is likewise important to consider all GHG emissions, because emissions of N_2O and CH_4 can be significant [23]. Accordingly, the net energy delivered per kg of CO_2 equivalent (CO_2-eq) emitted must as a minimum exceed that for the (fossil) fuel it is intended to replace. For example, corn ethanol must lower CO_2-eq emissions per MJ of fuel in the vehicle tank compared with those for petrol.

A further important question is *how* the available biomass should be used to maximise its carbon reduction potential. Should biomass not be used as fuel at all, but simply buried to sequester carbon? Or, should biomass be directly used for bioenergy, perhaps with carbon capture and sequestration (BECCS), to leverage its climate change mitigation? Or, should much non-food biomass first be used for biomaterials, then, if feasible, later combusted for bioenergy? We examine each of these options below.

6.1. Wood and Waste Burial

Zeng [64] has advocated that biomass should be simply buried deep underground. His idea would be "to thin forests regularly, and to bury excess wood, forestry waste and even trees that have been grown specifically to be buried in trenches between remaining trees" [65]. According to Zeng's calculations: "if we buried half of the wood that grows each year, in such a way that it didn't decay, enough CO_2 would be removed from the atmosphere to offset all of our fossil-fuel emissions" [65]. One risk is that CH_4 would be generated and released from the buried biomass by soil bacteria. And even if no decay occurred, nutrients would no longer be recycled to the forest, so fertilization may be needed.

A related approach, as promoted by Strand and Benford [66], would see agricultural crop residues collected, baled, transported and sequestered on the deep ocean floor (at depths > 1000–1500 m), weighed down with stone ballast if needed. The authors claimed that the "carbon sequestration efficiency" would be over 90%, compared with only 15% if the residues were left in the fields. But as discussed in Section 5.1, Karlen et al. [59], in a rejoinder article, have cast doubt on the efficacy of removing residues from the field for any purpose. Liska et al. [67] have likewise cautioned against use of crop redsidues, stressing loss of soil carbon. Their arguments would also apply to land waste burial.

Finally, these approaches are of no use for providing alternatives to fossil fuels; they are only useful for atmospheric carbon reductions. This point is important, since it is possible that, given a continuation of present trends, in a few decades time we will experience depletion of all but hard-to-extract fossil fuel reserves [1].

6.2. Direct Use of Bioenergy

Sanchez et al. [41], in their review of bioenergy climate mitigation potential in "western North America" showed that monetary costs for biomass feedstock for electricity production varied by an order of magnitude, with forest and agricultural residues far cheaper than dedicated feedstocks. This price variation suggests that CO_2 reduction potential (and its monetary costs) will show similar variation. Large reduction potential per MJ of energy would be expected in the case of methane extraction from municipal landfills or from sewage treatment plants. In such cases bioenergy receives a "double credit" for climate mitigation, since it can both reduce fossil fuel use and also negate the climate change effects of the methane emissions thereby avoided [10].

Many studies have examined the carbon reduction benefits of the US and Brazilian ethanol programs. These studies are important, since the data are derived from large-scale actual programs, rather than results derived from experimental plots or mathematical models. For the US corn ethanol program, Wang and colleagues [48], using the GREET model, found that liquid biofuels for transport reduced GHG emissions compared with petrol, even when indirect effects from land use changes were included. Their results showed, however, that corn ethanol still released roughly 50-80% of the CO_2-eq per MJ that petrol did.

On the other hand, an increasing number of researchers are questioning the climate mitigation benefits of bioenergy, at least in some circumstances. Searchinger et al. [68] have argued that the *indirect* effects on land use of using food crops for bioenergy greatly reduce bioenergy carbon mitigation. For Smith et al. [23], emissions from soils of nitrous oxide (N_2O)—a powerful and long-lasting GHG—would itself largely negate any carbon reduction benefits. West et al. [69] have further pointed out that if the new land needed for agriculture is in the tropics, as is likely, the soil carbon losses will be far higher than if the same amount of food was grown on temperate regions. Popp et al. [70] have also stressed the uncertainty surrounding the GHG reduction potential of bioenergy.

Roder et al. [71] examined whether bioenergy in the form of wood pellets from forest residues imported as a power station fuel to the UK from the USA, actually gave any carbon mitigation benefits at all. They concluded as follows: "The calculations showed in the best case results in GHG reductions of 83% compared to coal-fired electricity generation. When parameters such as different drying fuels, storage emission, dry matter losses and feedstock market changes were included, the bioenergy emission profiles showed strong variation with up to 73% higher GHG emissions compared to coal. " The lower yields per hectare found by Searle and Malins [54] also imply both much lower net energy return and carbon mitigation benefits.

Should biomass be converted to liquid transport fuels, or used as a power station fuel, perhaps with combined heat and power (CHP)? At present, more bioenergy is converted to liquid fuels (ethanol and diesel) than is used as a power station or CHP fuel [2,3]. As already noted, energy security, rural incomes and urban air pollution reduction were important factors driving corn ethanol production in the US, in addition to CO_2-eq reductions noted by Wang et al. [48]. However, Campbell et al. [72] have made the case that greater climate benefits can be obtained for road transport if biomass is used to produce electricity instead: "Bioelectricity produces an average of 81% more transportation kilometres and 108% more emissions offsets per unit area of cropland than does cellulosic ethanol." So, just as change of diet would enable greater carbon reductions from bioenergy, so would change in end use of cellulosic fuels from liquid transport fuels to electricity production.

Sanchez et al. [41] have argued that "BECCS may be one of the few cost effective carbon-negative opportunities available should anthropogenic climate change be worse than anticipated or emissions reductions in other sectors prove particularly difficult." In research done for the latest IPCC report, van Vuuren et al. [73] modelled the RCP2.6 pathway, designed to limit average global temperature increases to 2 °C above pre-industrial. They also envisaged a major role for bioenergy in climate mitigation, and particularly for BECCS, along with CCS for remaining fossil fuel use over the present century. BECCS was seen as greatly extending bioenergy's role in climate mitigation. Creutzig et al. [49] have assembled data showing how bioenergy plantation feedstock for electricity production can have far greater CO_2-eq reduction per MJ of electricity compared with fossil fuel electricity if BECCS is also used. Compared with modern coal-fired electricity plants, bioelectricity plants, both without CCS, resulted in reductions of from 0.165–0.245 kg CO_2-eq per MJ of electricity, depending on biomass feedstock. When both plants were provided with CCS, the corresponding reduction figure rose to 0.22–0.27 kg.

If BECCS is implemented, the energy costs of capturing and permanently storing bioenergy CO_2 emissions will reduce the net energy available from biomass, but enhance its CO_2-eq reductions. For climate mitigation, whether employing BECCS increases or reduces net GJ/tonne CO_2-eq is the relevant question. However, BECCS implies that CCS for fossil fuels is also feasible from technical, political, and economic viewpoints. If it is, BECCS will then need to compete with fossil fuels, especially coal, since the CCS technology and costs are identical for the two fuels, and indeed, for co-firing, would occur in the same power plant. Anderson [74] has, however, cautioned about relying on BECCS, an untried technology, as a major plank in climate mitigation. In fact, geological sequestration of CO_2 in general faces many serious problems [1], which perhaps helps explain why no large-scale CCS-equipped generating plants are in operation.

6.3. Dual Use: Biomaterials and Bioenergy

In Section 4 it was shown that although biomaterials were losing share in the construction sector, their use instead of concrete, steel, or other construction materials would often allow a given building function to be met at a lower CO_2-eq cost, resulting in lower overall emissions from the construction sector in general. In addition, to a far greater extent than, for example, concrete, timber can often be recycled for re-use as a building material. Steel can also be recycled of course, but its reprocessing still involves major energy and GHG costs.

Two questions arise in combusting biomaterial wastes. First, would collection and transport costs negate any further GHG reduction benefits? Cities have both high areal intensities of both materials use (tonne/km^2) and energy use GJ/km^2), and further incur substantial waste collection and disposal costs. Transport costs should therefore be minor, and would be offset by reduced waste to landfill transport costs. Second, to what extent would the often toxic preservatives and bonding agents used for biomaterials reduce the quantity available for combustion? Pizzi [75] has shown, however, that non-toxic substitutes are available for both preservatives and bonding agents.

6.4. Timescales

In addition to the issues already raised in Sections 6.1–6.3, an important factor to consider in assessing the different approaches to its use is the time taken to achieve the mitigation outcome [76]. Time-to-harvest will be shortest for biofuel production, given that this typically uses feedstocks consisting of seasonal crops (eg sugar cane, corn, palm, rapeseed). For woody biomass, which can be used as a substitute material in buildings, and later for energy production, time-to-harvest will depend on species type, land quality and the ultimate purpose of the material (eg manufactured and engineered timbers, structural timber, cladding, panelling, decking). Plantation timber harvest times range from 10 to 60 years, with longer times generally needed to achieve the log size suitable for structural timber. An as example, *radiata* pine, a fast growing softwood species commonly used in the housing construction sector, is typically harvested after 30 to 35 years of its initial planting [77]. During the growth period, lower grade timber is harvested from these plantations during pruning and thinning operations; this timber could be used directly as a bioenergy feedstock if deemed unsuitable for wood products. The proportion of the plantation harvested in this manner depends entirely on the ultimate use of the dominant plantation product [77].

The time taken to achieve the additional benefit in CO_2 mitigation by material substitution will depend on the life of the building in which it is used. For residential housing, although there will be refurbishment throughout its life, it could take up to 100 years to release the structural wood (eg floor, ceiling and walls) for final use in energy production [76]. Depending of type of antifungal treatment used, timber used externally (eg decking, fencing and cladding), could be released for energy production much sooner.

Table 4 presents a summary of the foregoing discussion, and also includes an indication of the potential EROEI for the biomass utilisation pathway.

Table 4. Summary of biomass climate mitigation potential and indicative EROEI.

Biomass ultilization pathway	Atmospheric removal of CO_2	Reduction in CO_2 emissions by material substitution	Reduction in CO_2 emissions by fuel substitution	EROEI
Burial	X			Negative
Bioenergy (inc. biofuels)			X	Low to medium
Material + burial	X	X		Low
Material + bioenergy		X	X	Medium
Material + bioenergy + CCS	X	X	X	Low to medium

7. Discussion and Conclusions

Humans use biomass products for food, fodder, energy and materials, but their combined use may already be near limits. Further, on-going climate change could change NPP at various scales, either through temperature or rainfall changes. The likely future climate changes will on balance negatively affect yields [78], and thus biomass potential [79]. Hence the important question addressed in this review: How should non-food biomass be deployed to maximise reductions in GHGs?

The use of biomass for biomaterials has been largely ignored, the implicit assumption being that it will continue to lose market share. But increasing biomaterials' share of the materials market can in many cases reduce GHG emissions by displacing production of more energy-intensive (and GHG-intensive) competing materials such as concrete and steel, or artificial fibres. However, it will not necessarily achieve greater GHG reductions than directly using the biomass for energy, which also displaces fossil fuels. We have argued here for dual use of non-food biomass, first using biomass for various materials applications, perhaps followed by reuse, then finally combusting it for energy at the end of its useful life. Dual use would potentially enable such bioenergy to pass the EROEI test, since only the extra energy (and GHG) costs involved in collection are relevant. Since even food production generates wastes, some of which at least can be used for energy, the different uses for biomass can partly conflict, partly complement each other.

This review has made little mention of monetary costs of biomaterials or bioenergy compared with alternatives. The reason is that today's costs may be a poor guide to future costs, particularly if carbon taxes are introduced. If these taxes were high, the monetary costs of using biomass for materials and/or energy would compare more favourably with alternatives. Fossil fuels also receive very high subsidies globally [80].

The conclusion is that the scope of analysis for bioenergy's global potential and carbon mitigation potential has to be widened even further. The global potential for bioenergy in recent decades would have risen because of the declining global market share of biomass materials. Evaluating the carbon reduction potential of biomass is now seen to require consideration of global GHG emissions from both the entire non-food biomass system *and* from the non-biomass materials sector (as well as the GHG costs of biomaterials waste disposal). However, the emissions reduction from final combustion of biomaterials could be delayed for decades, too late if reductions in GHGs are urgently needed.

A useful analogy may be water recycling [81]. In the face of looming water shortages, some researchers propose reusing water in a series of uses, with each successive use needing lower water quality. Finally, after the water is piped to a treatment plant, the cycle is repeated. For construction timber, reuse for construction or other material use is also often possible, with final combustion for energy analogous to the water treatment plant, although unlike water, no further reuse is possible after combustion.

Conflicts of Interest

All authors declare no conflicts of interest in this paper.

References

1. Moriarty P, Honnery D (2011) *Rise and Fall of the Carbon Civilisation*. London, Springer.
2. BP (2016) *BP Statistical Review of World Energy*. London, BP.
3. International Energy Agency (IEA) (2016) *Key World Energy Statistics 2016*. Paris, IEA/OECD.

4. Foley JA, Monfreda C, Ramankutty N, et al. (2007) Our share of the planetary pie. *PNAS* 104: 12585-12586.
5. Kleidon A (2006) The climate sensitivity to human appropriation of vegetation productivity and its thermodynamic characterization. *Glob Planet Change* 54: 109-127.
6. Krausmann F, Erb K-H, Gingrich S, et al. (2013) Global human appropriation of net primary production doubled in the 20th century. *PNAS* 110: 10324-10329.
7. Running SW (2012) A measurable planetary boundary for the biosphere. *Science* 337: 1458-1459.
8. Schramski JR, Gattie DK, Brown JH (2015) Human domination of the biosphere: rapid discharge of the earth-space battery foretells the future of humankind. *PNAS* 112: 9511-9517.
9. Moriarty P, Honnery D (2009) What energy levels can the Earth sustain? *Energy Policy* 37: 2469-2474.
10. Moriarty P, Honnery D (2007) World bioenergy: problems and prospects. *Int J Glob Energ Issues* 27: 231-249.
11. Hein L, Leemans R (2012) The impact of first-generation biofuels on the depletion of the global phosphorus reserve. *Ambio* 41: 341-349.
12. Smeets EMW, Faaij APC, Lewandowski IM, et al. (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog Energ Combust Sci* 33: 56-106.
13. Erb K-H, Haberl H, Plutzar C (2012) Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. *Energy Policy* 47: 260-269.
14. Thrän D, Seidenberger T, Zeddies J, et al. (2010) Global biomass potentials—Resources, drivers and scenario results. *Energ Sustain Dev* 14(3): 200-205.
15. Searchinger T, Edwards R, Mulligan D, et al. (2015) Do biofuel policies seek to cut emissions by cutting food? *Science* 347: 1420-1422.
16. OECD/FAO (2014) *OECD-FAO Agricultural Outlook 2014-2023*. Paris, OECD. Available from http://dx.doi.org/10.1787/agr_outlook-2014-en.
17. Alexandratos N, Bruinsma J (2012) *World Agriculture Towards 2030/2050: The 2012 Revision*. ESA Working Paper No. 12-03. Rome, FAO.
18. Burney JA, Davis SJ, Lobell DB (2010) Greenhouse gas mitigation by agricultural intensification. *PNAS* 107: 12052–12057.
19. Acker TL, Atwater C, Smith DH (2013) Energy inefficiency in industrial agriculture: you are what you eat. *Energ Sources Pt B: Econ Planning Pol* 8: 420-430.
20. Pelletier N, Tyedmers P (2010) Forecasting potential global environmental costs of livestock production 2000–2050. *PNAS* 107: 18371-18374.
21. Haberl H, Beringer T, Bhattacharya SC, et al. (2010) The global technical potential of bio-energy in 2050 considering sustainability constraints. *Curr Opin Environ Sustain* 2: 394-403.
22. Powell TWR, Lenton TM (2012) Future carbon dioxide removal via biomass energy constrained by agricultural efficiency and dietary trends. *Energ Environ Sci* 5: 8116-8133.
23. Smith KA, Mosier AR, Crutzen PJ, et al. (2012) The role of N_2O derived from crop-based biofuels, and from agriculture in general, in Earth's climate. *Phil Trans Roy Soc B* 367: 1169-1174.
24. Ruan L, Bhardwaj AK, Hamilton SK, et al. (2016) Nitrogen fertilization challenges the climate benefit of cellulosic biofuels. *Environ Res Lett* 11 (064007).

25. Zhao G, Bryan BA, King D, et al. (2015) Sustainable limits to crop residue harvest for bioenergy: maintaining soil carbon in Australia's agricultural lands. *Glob Change Biol: Bioenerg* 7: 479-487.
26. Van Renssen S (2014) A bioeconomy to fight climate change. *Nature Clim Change* 4: 951-953.
27. Umweltbundesamt (2014) Environmental Innovation Policy – Greater resource efficiency and climate protection through the sustainable material use of biomass. Available from: http://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_03_2014_druckfassung_uba_stofflich_abschlussbericht_kurz_englisch.pdf.
28. Hoogwijk M, Faaij A, van den Broek R, et al. (2003) Exploration of the ranges of the global potential of biomass for energy. *Biomass Bioenerg* 25: 119-133.
29. Carmichael A (2015) Man-made fibers continue to grow. *Textile World*. Available from: http://www.textileworld.com/textile-world/fiber-world/2015/02/man-made-fibers-continue-to-grow/.
30. World Economic Forum (WEF) (2016) The new plastics economy: rethinking the future of plastics. WEF. Available from: http://www3.weforum.org/docs/WEF_The_New_Plastics_Economy.pdf.
31. Gustavsson L, Sathre R (2011) Energy and CO_2 analysis of wood substitution in construction *Clim Change* 105: 129-153.
32. Bribián IZ, Capilla AV, Usón AA (2011) Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. *Build Environ* 46: 1133-1140.
33. Warman RD (2014) Global wood production from natural forests has peaked. *Biodivers Conserv* 23: 1063-1078.
34. World Steel Association (2015) Steel statistical yearbook 2015. Available from: https://www.worldsteel.org/statistics/statistics-archive/yearbook-archive.html. Also earlier editions.
35. Edwards P (2015) The rise and potential peak of cement demand in the urbanized world. Available from: http://cornerstonemag.net/the-rise-and-potential-peak-of-cement-demand-in-the-urbanized-world/.
36. International Aluminium Institute (2016) Primary aluminium production, 2016. Available from: http://www.world-aluminium.org/statistics/primary-aluminium-production/#data.
37. Food and Agriculture Organisation (FAO) (2014) Forestry products yearbook 2014. Rome: FAO.
38. Gustavsson L, Joelsson A (2010) Life cycle primary energy analysis of residential buildings. *Energ Buildings* 42: 210-220.
39. Gustavsson L, Pingoud K, Sathre R (2006) Carbon dioxide balance of wood substitution: comparing concrete- and wood-framed buildings. *Mitig Adapt Strategies Glob Change*11: 667-691.
40. Cornwall W (2016) Tall timber. *Science* 353: 1354-1356.
41. Sanchez DL, Nelson JH, Johnston J, et al. (2015) Biomass enables the transition to a carbon negative power system across western North America. *Nature Clim Change* 5: 230-234.
42. Van Vuuren DP, van Vliet J, Stehfest E (2009) Future bio-energy potential under various natural constraints. *Energ Policy* 37: 4220-4230.
43. Intergovernmental Panel on Climate Change (IPCC) (2015) *Climate Change 2014: Synthesis Report*. Cambridge UK, CUP.

44. Hall CAS, Lambert JG, Balogh SB (2014) EROI of different fuels and the implications for society. *Energ Policy* 64: 141-152.
45. Gasol CM, Gabarrell X, Anton A, et al. (2007) Life cycle assessment of a *Brassica carinata* bioenergy cropping system in southern Europe. *Biomass Bioenerg* 31: 543-555.
46. Murphy F, Devlin G, McDonnell K (2013) Miscanthus production and processing in Ireland: An analysis of energy requirements and environmental impacts. *Renew Sust Energ Rev* 23: 412-420.
47. de Castro C, Carpintero O, Frechoso F, et al. (2014) A top-down approach to assess physical and ecological limits of biofuels. *Energy* 64: 506-512.
48. Wang M, Han J, Dunn JB, et al. (2012) Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. *Environ Res Lett* 7: 045905, 1-13.
49. Creutzig F, Ravindranath NH, Bernde G, et al. (2015) Bioenergy and climate change mitigation: an assessment. *Glob Change Biol: Bioenerg* 7: 916-944.
50. Searle S, Malins C (2015) A reassessment of global bioenergy potential in 2050. *Glob Change Biol: Bioenerg* 7: 328-336.
51. Smith KW, Zhao M, Running SW (2012) Global bioenergy capacity as constrained by observed biospheric productivity rates. *BioSci* 62: 911-922.
52. Field CB, Campbell JE, Lobell DB (2008) Biomass energy: the scale of the potential resource. *Trends Ecol Evol* 23(2): 65-72.
53. Johnston M, Foley JA, Holloway T, et al. (2009) Resetting global expectations from agricultural biofuels. *Environ Res Lett* 4: 014004, 1-9.
54. Searle SY, Malins CJ (2014) Will energy crop yields meet expectations? *Biomass Bioenerg* 65: 3-12.
55. Slade R, Bauen A, Gross R (2014) Global bioenergy resources *Nature Clim Change* 4: 99-105.
56. Hennig C, Brosowski A, Majer S (2016) Sustainable feedstock potential—a limitation for the bio-based economy? *J Clean Prod* 123: 200-202.
57. Davis SC, Anderson-Teixeira KJ, DeLucia EH (2009) Life-cycle analysis and the ecology of biofuels. *Trends Plant Sci* 14: 140-146.
58. Canadell JG, Schulze ED (2014) Global potential of biospheric carbon management for climate mitigation. *Nature Comm* 5: 5282 (DOI: 10.1038/ncomms6282).
59. Karlen DL, Lal R, Follett RF, et al. (2009) Crop residues: the rest of the story. *Environ Sci Technol* 43: 8011-8015.
60. European Commission (2009) Renewable energy directive. EU 2009. Available from: https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive.
61. Hendrick MF, Cleveland S, Phillips NG (2016) Unleakable carbon. *Clim Pol.* Available from: http://dx.doi.org/10.1080/14693062.2016.1202808.
62. Pöyry Energy Consulting (2009) CO2 storage in depleted gas fields. A report to the IEA GHG R& D program. Available from: http://hub.globalccsinstitute.com/sites/default/files/publications/95786/co2-storage-depleted-gas-fields.pdf.
63. Fearnside PM (2015) Tropical hydropower in the clean development mechanism: Brazil's Santo Antônio Dam as an example of the need for change. *Clim Change* 131: 575-589.
64. Zeng N (2008) Carbon sequestration via wood burial. *Carbon Balance Manag* 3(1).
65. Lovett R (2008) Carbon lockdown. *New Sci* 3: 32-35.

66. Strand S, Benford G (2009) Ocean sequestration of crop residue carbon: Recycling fossil fuel carbon back to deep sediments. *Environ Sci Technol* 43: 1000-1007.
67. Liska AJ, Yang H, Milner M, et al. (2014) Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions. *Nature Clim Change* 4: 398-401.
68. Searchinger TD, Estes L, Thornton PK, et al. (2015) High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. *Nature Clim Change* 5: 481-486.
69. West PC, Gibbs HK, Monfreda C, et al. (2010) Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. *PNAS* 107: 19645-19648.
70. Popp J, Lakner Z, Harangi-Rákos M, et al. (2014) The effect of bioenergy expansion: food, energy, and environment. *Renew Sust Energ Rev* 32: 559-578.
71. Roder M, Whittaker C, Thornley P (2015) How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass Bioenerg* 79: 50-63.
72. Campbell JE, Lobell DB, Field CB (2009) Greater transportation energy and GHG offsets from bioelectricity than ethanol. *Science* 324: 1055-1057.
73. Van Vuuren DP, Stehfest E, Elzen MG, et al. (2011) RCP2.6: exploring the possibility to keep global mean temperature increase below 2 °C. *Clim Change* 109: 95-116.
74. Anderson K (2015) Duality in climate science. *Nature Geosci* 8: 898-900.
75. Pizzi A (2016) Wood products and green chemistry. *Annals Forest Sci* 73: 185-203.
76. Fouquet M, Levasseur A, Margni M, et al. (2015) Methodological challenges and developments in LCA of low energy buildings: Application to biogenic carbon and global warming assessment. *Build Environ* 90: 51-59.
77. Mead J (2013) Sustainable management of radiata pine plantations. FAO Forestry Paper 170, Available from: http://www.fao.org/docrep/018/i3274e/i3274e.pdf.
78. Mora C, Caldwell IR, Caldwell JM, et al. (2015) Suitable days for plant growth disappear under projected climate change: potential human and biotic vulnerability. *PLoS Biol* 13(6): e1002167.
79. Moriarty P, Honnery D (2011) Is there an optimum level for renewable energy? *Energy Policy* 39: 2748-2753.
80. Moriarty P, Honnery D (2017) Sustainable energy resources: prospects and policy. Chapter 1 in M.G. Rasul et al. (Eds) *Clean Energy For Sustainable Development.* London, Academic Press/Elsevier.
81. Adee S (2016) Not a drop to drink. *New Sci* 13: 16-17.