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PERSPECTIVE

Ecological impacts and limits of biomass use: a critical review

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Abstract

Conventional biomass sources have been widely exploited for several end uses (mostly food, feed, fuel and chemicals). More unconventional sources are continually being sought for meeting the growing planetary demands for biomass materials. Biofuels are already commercially produced in many countries and are becoming mainstream. The role of biorefineries for production of chemicals is also on the rise. Plant biomass is the primary source of food for all multicellular living organisms. Primary production remains a key link in the chain of life support on planet Earth. Is there enough for all? What new strategies (or technologies) are available or promising for providing plant biomass in a safe and sustainable way? What are the potential impacts (footprints and efficiencies) of such strategies? What can be the limiting factors—land, water, energy and nutrients? What might be the limits for specific regions (OECD vs. non-OECD, advanced vs. developing, dry and warm vs. wet and cool, etc.). In this paper, we provided answers to these questions by critically reviewing the pros and cons associated with current and future production and use pathways for biomass. We conclude that in many cases, the jury is still out, and we cannot come to a solid verdict about the future of biomass production and use.

Keywords Bioenergy · Food · Feed · Resource footprints · Waste management · Multifunctional land use

Introduction

Historically humans were dependent on biomass. We can argue that the origins of human civilization come from plant biomass (henceforth, biomass refers to plant biomass). Deforestation in Europe was rapidly changing the landscape till the beginning of the industrial era (Kaplan et al. 2009). Forests were removed to give space to agriculture (Williams 2000) but also for timber products and firewood (Reboredo and Pais 2014). Agriculture was introduced as a means to increase production of biomass. Total terrestrial net primary production (NPP) is estimated at 2190 EJ/year or 118 billion tonnes of dry matter/yr, whereas the above-ground terrestrial NPP is reported as 1241EJ/year or 67Gt/yr (Rogner et al. 2012). Some sources put the above-ground terrestrial NPP at 2200 EJ/year (Bang et al. 2013). Such difference between the estimates is mainly attributed to the difference in the carbon content of biomass and the difference in gross calorific value. Humans appropriate approximately 20.1 Gt/year (373 EJ/year) of biomass which equals to 17% of the total terrestrial NPP or 30% of the above-ground terrestrial NPP (Rogner et al. 2012). This certainly contributes to the overall destruction of the life support system on planet Earth, creating conditions for what some see as the sixth mass extinction (Ceballos et al. 2020).

Today, biomass is used for many purposes (Fig. 1) (Smeets et al. 2007; Arodudu et al. 2017a) where utilization varies based on (a) the source of biomass and (b) area of focus (Bang et al. 2013; Hiloidhari et al. 2014), making an accurate estimation of competing uses very difficult. For instance, major uses of straw in the UK can be animal feed, bedding and bioenergy applications (Bang et al. 2013), in India, depending on the straw, it can be also used as packing material (Hiloidhari et al. 2014). Aside from food-related uses, which rank the highest in terms of priority, biomass can be used as soil mulch cover, soil stabilizer, green manure and mushroom substrate, it is essential to maintain biodiversity and wildlife (Scarlat et al. 2010; Arodudu et al. 2017b),

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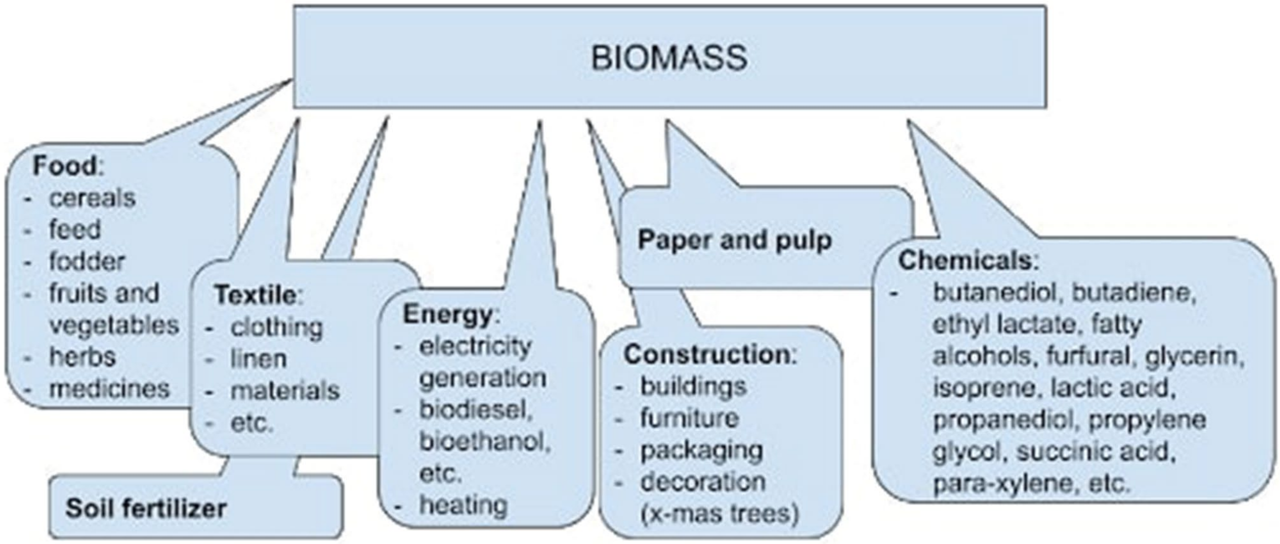

Fig. 1 Competing uses of biomass

and it is also an essential raw material and feedstock for industrial processes (Arodudu et al. 2013; Krausmann et al. 2017), especially for energy, construction and chemical production (Haas et al. 2015).

These uses are particularly important in an age when the global economy seeks to transit from fossil energy carriers (which accounts for about 80% of global primary energy) to renewables (IEA 2019). This is primarily because of concerns about climate change, but is also driven by growing risks associated with depletion of cheap and easily extractable global fossil reserves (petroleum, coal and natural gas) over the last centuries impacting the reliability of their supplies, creating energy market instability and price volatility (Poisson and Hall 2013; Lambert et al. 2014). Considering that the prominent energy scenarios suggest that energy consumption will only increase in the future (USEIA 2019), and growing interest in renewable sources with lower GHG emissions, using biomass for energy production has again, as two centuries ago, become mainstream.

Bioenergy

Bioenergy refers to energy obtained from any form of materials derived from biological sources and is the single largest source of renewable energy used today. Solid biofuels (e.g., charcoal, fuelwood, wood residue/by-products, black liquor, bagasse, animal waste, vegetal residue/material, renewable fraction of industrial waste, etc.), liquid biofuels, biogas and renewable municipal waste together provide 9.2% of the world's total primary energy supply (IEA 2019). However, within the renewable energy supply, the share of solid biofuels (mostly charcoal) is 60.7%; liquid biofuels supply 4.6%, biogas 1.7% and renewable municipal waste 0.9% (IEA 2019). Given the widespread use of solid biofuels in developing countries, non-OECD countries are logically the largest suppliers of solid biofuels (IEA 2019). Around 2.8 billion people in 2010 relied on solid fuels for cooking, 78% of them lived in rural areas, mostly in Africa and Asia (SE4ALL 2013). In contrast, OECD countries are the main suppliers of biogas, liquid biofuels and renewable municipal waste (IEA 2019). Allocation of biomass for bioenergy amounts to 35–55 EJ/year (Haberl et al. 2007) or between 2.8% and 4.4% of the above-ground terrestrial NPP. Other studies report the current uses in a similar range. For instance, Parikka (2004) put the total energy potential from biomass at 103.8 EJ/year and current uses at 39.7 EJ/year (38% of the total potential), while Daioglou et al. (2016) put the total energy potential from biomass at 116 EJ/year and current uses at 33 EJ/year (28% of the total potential).

Bioenergy use in developing versus developed countries is different. In developing countries with historical bioenergy use, people rely on biomass for cooking because they have no other choice (SE4ALL 2013). In contrast, OECD countries share of solid biofuels is smaller, while share of liquid biofuel and biogas use is larger than the global averages (IEA 2019). Electricity generation rarely uses solid biofuels, and the share of electricity produced from biofuels and renewable municipal waste is therefore larger in OECD countries than the global average, i.e., 2.8% vs 2% in 2017 (IEA 2019). The environmental impact of bioenergy use in developing countries and developed countries is very different because of the kinds of uses. Using solid biomass collected from the neighboring areas for cooking or heating can have local impacts, such as indoor pollution, and labor-intensive collecting can limit women and children's time for education and other activities (IEA 2017). The traditional use of biomass in basic stoves or open fires also leads to very inefficient use of the resource, e.g., 5–15% (IEA 2017).

Land, water and carbon footprints of bioenergy may be too large. For instance, using liquid biofuel or biogas for decarbonization of GHG intensive sectors by replacing fossil fuels (IEA 2017), entails energy inputs associated with large land, water footprints (Rulli et al. 2016; Holmatov et al. 2019) and carbon emissions (Kauffman et al. 2011; Holmatov et al. 2019).

Bioenergy can have both positive and negative impacts on the immediate surrounding environment at the local and global scales that come with many strings attached. Generally speaking, increasing conventional bioenergy production can contribute to higher energy security, create employment opportunities, but on the other hand, as well illustrated by the recent movie 'Planet of the Humans,' can lead to deforestation, increase GHG emissions, environmental degradation and even negatively affect food security (Beringer et al. 2011). An example of the positive effect is that willow and poplar plantations could attract species from the surrounding areas and can hold more diversity than coniferous forests and arable lands (Baum et al.2009). An example of the negative effect is that promoting bioenergy production can create a lock-in effect (expected payback time of investments is long), thereby bioenergy will then have to be produced for a longer period than intended with consequent complications.

We also need to keep in mind the temporal dimension: While in the long run bioenergy can be considered as carbon neutral, there is a significant time lag between the GHG emissions that may be happening now, when biofuels are burned, and the following carbon sequestration later on, when carbon dioxide molecules are removed from the atmosphere through photosynthesis. This is especially the case when perennial vegetation is used as feedstock. The land footprint of consumption (including bioenergy) is especially critical in places where 'biocapacity' is exceeded (Borucke et al. 2013; Wackernagel et al. 1999; Wackernagel and Rees 1998). Areas with sufficiently high NPP may also have high potential evapotranspiration (mostly dry and warm regions) which may subsequently result in water scarcity issues (Beringer et al. 2011).

Global Biomass

Logistical issues associated with biomass are numerous and complex. Cost of the supply chain and technology for converting biomass to useful forms of energy are important barriers (Rentizelas et al. 2009). In addition, energy conversion technologies can be sensitive to using a mix of different biomass types (Rentizelas et al. 2009), while homogenous biomass in a given geographic area can be limited and seasonal. Moisture of biomass is another important factor, whereby fresh biomass can have high moisture that is not suitable for certain energy uses (i.e., fresh wood moisture at 35–60% is higher than 5–20% used for combustion (Ragland et al. 1991)).

At planetary scale, climate change can have a large impact on biomass production. For instance, climate change can lead to decrease in irrigated land (Zhang and Cai 2011; EEA 2019; Worqlul et al. 2019), affect crop productivity, due to altered precipitation, temperature, soil conditions, etc. (Edenhofer et al. 2011). At the same time, the global environmental (GHG, water and land use) footprint of the agriculture sector is huge and it impacts climate change in many ways. The present-day hierarchy of uses of global biomass is for feed (58%), bioenergy (heat and power—16%), food (14%), materials (10%) and biofuels (transport fuels, e.g., biodiesel and bioethanol—1%) (Piotrowski et al. 2015). Animal production (meat production especially) has the largest environmental footprints within the agriculture sector; hence, the rise in the production of plant-based meats is expected to lower its environmental footprints. This, however, might also be a trade-off, as the carbon, water and land use footprints of plant-based ingredients for production of plant-based meat should also be expected to rise.

More recent excitement has been with the use of biomass for replacement of several fossil based materials (Chen and Patel 2012; Llevot et al. 2016; Bensabeh et al. 2020). Intensive research is happening on synthesis of polymers and monomers from biomass (Llevot et al. 2016). While biomass can be used to make nearly any chemical building blocks of plastics, most of the processes are commercially unfeasible and bio-based chemicals make up only about 5% of all chemicals (Harmsen et al. 2014). The true scale of biomass use for production of various materials is disparate, incomplete or not sufficiently detailed (Nattrass et al. 2016); however, an estimated 130 million tonnes (dry matter) or 1.14% of the global biomass supply (out of the total of 11.4 billion tonnes dry matter in 2011) is used in the chemical industry with the share of bio-based polymers currently being insignificant (Piotrowski et al. 2015). The production of bio-based plastics is set to displace conventional plastic packaging within the next decade (Yates and Claire 2013; Papadopoulou et al. 2019). Coca-Cola and other companies are announcing a major shift to bioplastic made of wood chips, straw and food waste (Carrington 2018; Avantium 2020), a process which will only increase the demand for biomass (Smith et al. 2013; Mayer et al. 2017). Much of the drive towards bio-based plastic is the concern with plastic pollution and the expectation that the alternative polymers will be biodegradable—the promise which is far from being always delivered since not all bio-polymers are easily degradable (Tokiwa et al. 2009).

Circular bioeconomy strategies around the world (Europe especially) emphasizes the need to replace fossil and other non-renewable energy and material resources with renewables (mostly biomass) (EC 2015). Noteworthy, however, is the fact that biomass has played an increasingly lower role in global material consumption over the last century (Krausmann et al. 2009, 2017, 2018). According to Krausmann et al. (2009), its share in total material consumption has declined from almost three quarters in 1900 to only one-third about a century later. For most of the twentieth century, biomass was the most significant of the four material types (others being fossil energy carriers, ores and industrial minerals and bulk minerals for construction) in terms of mass and only in the 1990s was it overtaken by construction minerals (Krausmann et al. 2009, 2017). The period between World War II and the first and second oil price peaks in the early 1970s saw a rapid shift from renewable biomass towards mineral materials. Biomass experienced relative peaks in 1920, 1933 and 1946 due to fall in the use of the other materials and not because of significant increase in biomass extraction. These reductions in material extraction induced by World War I and World War II were less pronounced for biomass than for the other material categories. This is because of the relative importance of biomass as a source of food and animal feed. While the share of biomass in total material consumption declined over the last century, construction minerals (mostly sand and gravel used in concrete, foundations and base course layers as well as asphalt) grew by a factor of 34, while ores/industrial minerals extraction surged 27-fold (Krasumann et al. 2009, Krasumann et al. 2017). A continuous decline in the share of biomass to total material consumption globally is an indication it might not be able to replace other non-renewable materials used for energy, construction and chemical production (i.e., fossil minerals, as well as metallic and non-metallic minerals), thereby restricting its primary use to food, animal feed and other daily or seasonal consumptive and dissipative uses (e.g., animal bedding, packaging material, etc.).

Based on business as usual projection, materials extracted and used worldwide are expected to rise from 89 Gt/yr in 2015 to 218 Gt/yr by 2050 (Krausmann et al. 2018). Considering the already massive depletion, impending extraction peaks and near extinction of global fossil and other non-renewable resources, there are only three options going into the future. These include.

1. Reducing material consumption through massive trade-offs by humans and changing consumption patterns;
2. Meeting projected material by reliance on reuse and recycling of current non-renewable material stocks and wastes (which is currently insufficient, as larger component of material stocks are still primary materials);
3. Replacement with renewable biomass, notwithstanding its decreasing share in global material extraction mix, as well as projected future increase in demands for use in its traditional role as source of food, animal feed and other dissipative uses (Haas et al. 2015; Mayer et al. 2017; Le Noë et al. 2020).

Most likely we will see a combination of these three strategies, with #1 being certainly the most sustainable one, yet the hardest to implement. Wastes from material extraction and consumption have grown at a slower pace over the last decades despite accelerated increase in total domestic material consumption (DMC) globally (Krausmann et al. 2009). This was due to increased material stock accumulation in buildings, infrastructures, manufactured machineries, as well as durable goods (Krausmann et al. 2018). These material stock accumulations were facilitated by a century of economic boom, urbanization and industrialization in Europe, Japan, the USA and other high-income countries post-World War II (Krausmann et al. 2017). This suggests that even though there is much waste for reuse and recycling (35% of extraction and consumption), far more is going into material stock accumulation than available continually for reuse and recycling (Krausmann et al. 2018). The majority of the recycling flow comprises nonmetallic minerals (88% in 2010), which are mainly down-cycled as base materials for backfilling during new construction. Metals, biomass and plastics together account for 12% of total end-of-life recycling (Krausmann et al. 2017). Despite growth in global material extraction and consumption demand, the contribution of recycling to closing material loops has remained lower than the promising potential suggested by end-of-life recycling rates. For non-metallic minerals, even though 37% of all end-of-life outflows are recycled, only a recycling input rate of 11% is achieved (Graedel et al. 2011; Krasumann et al. 2017). For metals, even though 77% of end-of-life outputs are recycled (because recycling in the metal industry is more advanced), the recycling input rate is only 27% (Zimring 2009; Oldenzie and Weber 2013). This is an indication of the limits of reuse and recycling of non-renewable materials going forward. Replacement with renewable biomass at the projected scale should therefore be expected to entail significant increase in production and use of biomass, as well as reuse and recycling of biomass waste, and hence the strategies and technologies that we analyzed in this study.

However, despite biomass renewability, limitations about its potential also exist. Global biomass appropriation (also known as the human appropriation of net primary production (HANPP), which include harvesting or burning biomass (for food, animal feed, energy and other dissipative uses), as well as conversion of natural ecosystems to managed lands with lower productivity, has only doubled between 1910 and 2015, despite fourfold increase in human population and 17-fold economic output (Krausmann et al. 2013). According to Krausmann et al. (2013), despite an increase in land's productive capacity and biomass appropriation efficiency as a result of land use practices over the last century, biomass harvested per capita and year slightly declined even though there was growth in total biomass consumption. This is because there was a decline in reliance on bioenergy due to higher conversion efficiencies of both bioenergy and fossil energy resources. The rise in HANPP efficiency can be attributed to increased crop yields due to increased fossil energy inputs and substantial ecological costs such as soil degradation and biodiversity loss. If humans can maintain the past trends in efficiency gains, we estimate that HANPP might only grow by 27–29% by 2050. Larger bioenergy extraction could, however, increase global HANPP to 44% (Krausmann et al. 2013), and this is also expected to be at significant ecological costs. Increasing biomass production despite land use efficiency gains and land intensification might still fall short of meeting extraction and sustainability needs of other categories that humanity direly seeks replacement for. Even though an increase in production is required, a prioritization of available or grown biomass stocks (via reallocation, redistribution, reuse and recycling) will be essential to avoid wasting resources and to maximize their use.

According to Krausmann et al. (2013), Latin America and Africa with moderate and low biomass yields, respectively, experienced the highest yield gap over the last century. In other words, Latin America and Africa are the two regions yet to maximize their biomass efficiency potentials from land use practices. Asia, Europe and North America that have maximized their global biomass productivity potential by pushing against planetary boundaries (via land use practices) at significant energy and ecological costs (e.g., soil degradation, biodiversity loss, etc.) over the last century are expected to have limited (low to moderate) biomass or HANPP efficiency gains in the future. Latin America and Africa on the other hand have more untapped HANPP efficiency gain potential (moderate to high) which can be further exploited by employing land use practices, which will again likely happen at the expense of biodiversity and natural capital.

Based on the findings by Krasumann et al. (2013), Erb et al. (2016a) and Erb et al. (2016b), we can infer that the potential for further biomass gains for human consumption through the application of land use practices is limited, if not almost exhausted for certain world regions (Erb et al. 2016a). Even though Erb et al. (2016a, b) found that efficient land use practices are capable of reducing the biomass turnover period by half of the expected payback time, noteworthy is the fact that this may not translate to net addition to or total recovery of global biomass stocks as demands will further shoot up in an era expected to put more pressure on biomass resources globally (i.e., global economic transition towards elimination of fossil fuel dependence, carbon neutrality and replacement of other non-renewables). Continuous search for ways of increasing biomass production will therefore not be the ultimate solution. Increasing its use efficiency by reallocation, redistribution, successive reuse and recycling of biomass waste (using available energy and material conversion technologies) before return to nature for maintenance of biological processes will have to be prioritized.

Questions and concerns

What strategies are available or promising for producing and using biomass in a safe and sustainable way? What are the impacts (footprints and efficiencies) of such strategies? What can be the limiting factor: land, water, soil, energy, nutrients, etc.? What might be the limits for specific regions? In answering these questions, we suggest the use of a systems thinking/intelligence approach for critical analysis of the capabilities and limitations of various strategies or technologies for food and animal feed production, as well as energy and chemical production.

Can we say that there is enough biomass for meeting food, feed, energy and chemical production demands, as well as providing for natural biological processes under a decarbonized circular economy? Around 820 million people in the world are still hungry (FAO et al. 2019) and closing this gap while facing uncertain challenges would entail setting priorities in terms of land use purposes (food, feed, biofuel, carbon storage, etc.). What strategies are available or promising for producing and using biomass in a safe and sustainable way? What are the impacts (footprints and efficiencies) of such strategies? What can be the limiting factor: land, water, energy, soil, nutrients, etc.?

While there is clear indication that the demand for biomass is likely to grow, we need to look for strategies that could increase the efficiency of human appropriation of biomass. We suggest that all technologies should be considered with three aspects in mind:

1. Gains and efficiencies—here we list the expected benefits from employing the technology and provide some estimate of its efficiency, ideally in terms of EROEI or productivity;
2. Limiting factors (land, water, energy, soil, nutrients, etc.) and impacts—what are the footprints associated with the technology, what are the costs and threats associated;
3. Regional limitations and preferences—OECD vs. non-OECD, advanced vs. developing, dry and warm vs. wet and cool, Global North vs. Global South, etc.

We may notice that in most cases, the impacts and consequences are quite interconnected, embedded in multiple feedback loops, which makes full cost and life cycle assessments only more difficult. For example, many technologies that improve biomass delivery for food come at the expense of using more energy, which in turn increases the demand for energy. Energy requirements then may be again estimated in terms of biomass needed to generate the energy used for food production, which should then be subtracted from the additional biomass produced.

Since one of the main uses of biomass by humans is for food, Table 1 presents some potential technologies and methods that may improve efficiency of agriculture, while preserving enough for biodiversity and nature conservation. While there are quite a few ideas under development and implementation, we can note that all of them have some limitations and there is obviously no silver bullet that can solve all problems.

Besides food and fiber, the second largest avenue of HANPP is bioenergy. This used to be for cooking and heating and has been largely replaced by fossil fuels. About 97% of bioenergy was obtained through direct combustion in 2004 (Demirbas 2004). Now, with the return to renewables we see an increasing demand for biomass for energy production. In Table 2, we reviewed some of the technologies that can make a difference in this domain.

In most cases, we still see a high reliance of these technologies on conventional fossil fuels, which requires careful EROEI accounting. The processes are generally limited by.

1. High costs of collection, transport and storage of biomass and higher local air emissions from movement of trucks (Sims et al. 2008);
2. Long 60–90 days turnover time in biogas plants for agricultural biomass (Klimiuk et al. 2010); and
3. Low efficiency whereby the biomethane production (from cellulose) achieves at best around 20% of energetical biomass utilization efficiency, which is much lower than converting it to other types of bioenergy (Iffland et al. 2015).

This can be avoided by building efficient source-to-plant pipeline systems for wet waste or installation of farm-, home- or market-based digesters (Arodudu et al. 2013), but will still require considerable economic incentives/subsidies, without which capital and operational costs for building infrastructure at sub-commercial scale (e.g., farm or home scale yielding limited supply of wet biomass) is impractical.

Most promising approaches are based on the following principles:

1. *Waste reduction and reuse* It is hardly efficient to produce bioenergy unless we use waste, by-products and plant residue as biomass. The EROEI is simply too low to justify the effort (Hall et al. 2011; Murphy et al. 2011). In this regard, it seems promising to organize cascades of use (increase in successive reuse and recycling) of organic waste. Forest residue/forest wood product waste, wastewater and sewage sludge, crop residues (including garden wastes and leaf fall), animal manure and food waste can be put in sequences of uses optimizing for the overall efficiency of biomass utilization.

   This promises an increased resource (material and energy) efficiency (Ciccarese et al. 2014; WWF 2016) and reduced carbon, water, land use and biodiversity impacts from lower deforestation and reduced land use change effects (Sikemma et al. 2013; Mair and Stern 2017). However, we should realize that recycling of resources entails costs and may slow down the economic processes (Haberl and Geissler 2000; Giampietro 2019). Collection and conversion technologies are yet to be improved. Implementation may be a challenge in less developed (non-OECD) countries without the necessary institutional and infrastructural framework and with no-access to the latest know-hows and patents.
2. *Co-production, multifunctional land use* For example, there is promise of co-production of renewable energy (wind and solar) with agricultural as well as residential, commercial, industrial and infrastructural land uses. Installing wind turbines or photovoltaics does not have to compromise the use of land as pasture, natural grasslands, forests, temporary and permanent croplands. In fact, in some cases it can be beneficial for biomass production and use.

   Solar panels and solar photovoltaic panels shade crops from heat stress and increase moisture absorption hereby aiding photosynthesis (Trainor et al. 2016; Barron-Gafford et al. 2019). Wind turbines can act as windbreaks, mix the air and regulate local day and night temperatures thereby helping crops to avoid heat stress in the day and frost at night (Inman 2010; Beckman and Xiarchos 2013). Wind turbines can make more carbon dioxide available to crops thereby aiding photosynthesis (CU 2010; ISU 2016). They can also reduce the amount of dew on leaves, thereby reducing incidences of fungal diseases in crops (Ames Laboratory 2010; Rajewski et al. 2016). While this is still applied mostly at experimental scale and is not yet widely practised (Inman 2010; Rajewski et al. 2016), there seems to be much potential for such co-production. Increased adoption of green roofs and retrofitting of old roofs in rural and areas for biomass production will also make more space available for solar panel and solar photovoltaic panel installations (Hernandez et al. 2014; Hoffacker et al. 2017).

   Similarly, urban agriculture and green buildings (Fig. 2) are other examples of multifunctional land use

Table 1 Strategies and technologies for producing, reallocating and redistributing biomass for food and animal feed production

Strategies (technologies)	Gains and efficiencies	Limiting factor (land, water, energy, soil, nutrients, etc.) and impacts	Regional limitations
Agricultural intensification	Doubling food and feed production on same land will save land use and increase green water efficiency (Zabel et al. 2014; Erb et al. 2016b) Not ideal but better than agricultural expansion via land use change (Bais-Moleman et al. 2019; Stanimirova et al. 2019)	Climate change (Lin et al. 2008; Campbell et al. 2014) Higher blue water, energy and carbon demands expected from fossil fuels, fertilizers and irrigation water (Mózner et al. 2012; Nemecek et al. 2011) The energy output in terms of food per unit of fossil based energy input or the EROI factor of intensive agricultural systems are low (Mohammad Shirazi et al. 2012) Very high nutrient pollution (Tilman 1999; Kröger et al. 2013; Ghosh et al. 2017)	Dry and warm regions are more susceptible to higher energy, nutrient (nitrogen and phosphorus) and water use (Beringer et al. 2011)
Regenerative agriculture[s]	Improves soil quality (Altieri and Nicholls 2008; Dougherty 2019), carbon and moisture content, resilience. Most suitable for organic agriculture. Also provides motivation to return to animal protein diet as against vegan diets (Gurian-Sherman 2019; Severson 2019)[b]	May need more land (Altieri et al. 2015; Regeneration International 2019), and time Risk of failure is high under continuous and/or extreme drought situations (Hüesker et al. 2011). Risk of failure may also increase with scale due to less supervision and oversight (Sternberg 2016)	
Urban vegetable gardening (hydroponics, aeroponics, fogponics, organoponics, aquaponics and anthroponics inclusive)	Creation of new carbon sinks and increased carbon sequestration capacity (Thornbush 2015; Mcdougall et al. 2020) Reduction of carbon and water needs of vegetable farming and saving land (Kulak et al. 2013)	Soil, indoor/outdoor climate and technology adopted (Gruda 2012, 2019; Gruda et al. 2019): some variations of urban gardening such as hydroponics may lead to higher energy consumption compared to traditional production systems (Martinez-Mate et al. 2018)	Roof and urban platform designs may be more contemporary, adaptable and suitable in advanced (OECD) countries than in developing (non-OECD) countries NPP (and hence the urban vegetable gardening potential) per unit of land is region specific and ranges from 0 to 3.5 kg dry matter m^{-2} depending on the conditions of the place (Haberl et al. 2004) and the growing technology adopted
Reclamation of desert and sand dunes for food and feed production—planting grasses and trees[c]. Zai Farming (dry basin farming)[d]	Reduction of global agricultural land use (Glenn et al. 1998; Leahy 2018) Improved soil formation and increase in biodiversity (Troung 1999; Wang et al. 2009). Increased carbon sequestration and sinks (Thomas et al. 2005; Yu et al. 2019) Reduction of nitrogen use—most suitable reclamation plants are legumes that fix nitrogen. Temperate species like poplar, willow, etc., and tropical species like gliricidia, leucaena, etc. (Fuwape and Akindele 1997; Wuehlisch 2011; Schweier and Becker 2013) are used	High demands for human labor Reclaiming substantial areas of sand dunes is a difficult task. While it may be more logical to reduce the pace of arable land degradation that currently reached 30–35 times that of its historic rate (UN 2020), reclaiming sand dunes is the only other option to abandonment of desert sand dunes and total loss of land for inhabitants of desert regions (Johnson 2006; Malagnoux 2007)	Mostly in dry and warm, developing (non-OECD) and Global South Countries Desertification is the underlying cause for religious extremism in the Sahel (Boko Haram, ISWAP-ISIS in West Africa), as well as Farmers-herders clashes. If there is no reclamation, regional security (across Sub-Saharan Africa) carbon sinks and biodiversity towards the equator will continue to be at risk

Table 1 (continued)

Strategies (technologies)	Gains and efficiencies	Limiting factor (land, water, energy, soil, nutrients, etc.) and impacts	Regional limitations
Reduced farm and forest mechanization (use of manual labor and smaller implements)	Carbon sequestration (Harvey and Brais 2002; McEwan et al. 2020) Reduced soil and ecosystem disturbance (Dykstra 2001; Poltoraka et al. 2018) Increased human labor (more jobs, more hazards) (Wood et al. 2003; Bluszkowska and Nurek 2014, Arodudu et al. 2017a) Higher accessibility to forest food and animal feed resources (namely fruits, mushroom, insects and game) (EPI-FAO 2010, FAO and UNEP 2020)	In some cases, lower yields and expansion into semi-natural land use	More feasible in smallholder farms and forests (higher in proportion and mostly found in developing, non-OECD and Global South countries) than in industrial farm and forest holdings (lower in proportion and mostly found in more developed, OECD and Global North countries)
Harvesting and growing seaweeds (algae) for animal feed production	Animal greenhouse gas reduction (Allen et al. 2001; Park 2020) Disturbance of marine ecosystem and reduced biodiversity (Pauly and Zeller 2016, Ritchie and Roser 2020), Cultivation of seaweeds is a solution for bioremediation of excess nutrients in eutrophic water bodies (Yan et al. 2017). It can take some the pressure off terrestrial production systems if done in marine environment (Wong and Cheung 2000; Garcia-Vaquero and Hayes 2016) More than 220 species of seaweed have commercial value and among these, about ten species are intensively cultivated (FAO 2018a)	Marine water biodiversity (Olafsson et al. 1995; Monagail et al. 2017) Land, energy, nitrogen, phosphorus and blue water (Boyd and Gross 2000; Boyd et al. 2005) Nutrient enrichment, oxygen depletion, water contamination and disease risks (Phillips 1990; Chapelle et al. 2000 Increase in carbon, energy, water and land use (Chojnacka 2008; Mulhollem 2019) Harvesting seaweed from the wild poses an issue of contamination with heavy metal (FAO 2018a) while growing seaweeds is not always feasible from the economic point of view (van den Burg et al. 2016)	Higher environmental burden on Global South where animal (cattle) meat production is driving deforestation and land use change Harvesting seaweeds is an important solution in areas where invasive seaweeds alter the composition of marine ecosystems, breed disease pathogens (e.g., Malaria mosquitoes on the Coast of West Africa), obstruct fishing activities and clog coastal waterways, thereby preventing the flow of economic activities (Honlah et al. 2019

Table 1 (continued)

Strategies (technologies)	Gains and efficiencies	Limiting factor (land, water, energy, soil, nutrients, etc.) and impacts	Regional limitations
Seafood harvesting and aquaculture	Since 1961, the annual growth in consumption of fish is growing two times faster than the population growth and exceeds annual growth in consumption of meat from all terrestrial animals (FAO 2018b) Seafood harvesting and aquaculture can reduce or replace dependence on livestock	Seafood harvesting has low energy efficiency (Tyedmers 2001; Guillen et al. 2016) and high energy consumption (Tyedmers 2000, 2004), Marine biodiversity loss (Bailey and Sumaila 2015), Land (Pelletier and Tyedmers 2007; Driscoll and Tyedmers 2010), Blue water (Pelletier and Tyedmers 2008 2011; Parker and Tyedmers 2012) 33% of marine fish stocks are fished at biologically unsustainable levels (i.e., overfished) and 35% of global fish catches are wasted or lost (FAO 2018b). In case of aquaculture: feed for farmed fish can include protein from wild fish creating a paradox; can cause local issues such as organic waste; lead to disease and parasite transmissions through interaction of wild and farmed fish species; may pose health risks by being contaminated with toxins and additives (Asche 2015). Destructive fishing can lead to biodiversity loss (Bailey and Sumaila 2015)	Higher environmental burden on developed, OECD Countries in the Global North due to higher import of and demand for seafood (Ellingson and Aanondsen 2006, Pelletier and Tyedmers 2010)
Plant based meat substitute production	Lower carbon, water and land use in comparison to animal meat production (Capritto 2019a; Newburger and Lucas 2019; Osmanski 2019) Healthier food in comparison to animal meat (contains fiber, no cholesterol but similar in calories and higher in sodium content) (Capritto 2019b, In, 2019) A range of plant-based proteins can substitute animal products and have better energy conversion efficiency than animal products where the energy feed conversion efficiency ranges from a low of 3.8% for beef to 25% for eggs (Alexander et al. 2016)	Associated increase in carbon, water, energy and land use of numerous plant-based ingredients and many production processes (Tugend 2019; López-Alt 2020) (Tilman et al. 2011, Erb et al. 2016b Low acceptance of consuming protein replacements. Even acceptance of meat replacement is still low (Elzerman et al. 2011), and the majority of the population is not expected to readily become vegetarian (Shepon et al. 2016). Moreover, the price of alternatives can be higher, i.e., the price of Beyond Meat is 3–4 times more expensive than the traditional meat products (Reinicke 2019)	Main impact of animal production (cattle especially) is not direct methane emission, but GHG emissions due to deforestation and land use change caused by rangeland expansion for animal production (Barona et al. 2010; Macedo et al. 2012). This scenario predominates in the tropics and Global South (Amazonian Basin) on a scale that can be considered significant (Lima et al. 2011; Aide et al. 2013)
Food waste prevention and valorization Redistribution and sharing (community fridges, stale food stores, refrigerating and/or packaging companies, community gardens, etc.), improved preservation and valorization (canning, brewing, souring, processing into home-made jam, marmalade, beer, etc.)	Lower food waste and higher food use efficiency (Davies et al. 2019; Davies and Evans 2019)	Heat, energy, climate change (FareShare 2017; Depta 2018) Community sharing may create social problems with the Commons (Hardin 1968), and result in unequal distribution of resources, in this case—storage space	Difficult to implement in energy poor, developing countries, where it might be needed most. Warm and wet countries face the challenge of quick ripening, over-ripening and quickening of agents of decay and rot

that can benefit biomass production. It has been shown that green roofs can also be considered as sources of biomass for bioenergy production (Arodudu et al. 2014). Domestic gardens and aquaculture (aquariums) can also be expanded. We already see how basements can be used to grow mushrooms (Corbin 2019). Another example is using roadside vegetation for bioenergy (Voinov et al. 2015).

3. *Decreasing consumption and waste, demand-side incentives* The most radical solution to biomass overuse is decreasing our overall consumption of resources. This is especially relevant for the rich OECD world, where consumption has been disproportionately high and excessive. Food waste alone amounts to 1.3 billion tonnes per annum (Bos-Brouwers et al. 2012). Resources used for food production that are lost or wasted globally add up to 4.4 gigatonnes of GHG, that is more than emissions from all countries but the USA and China (Rezaei and Liu 2017).

   The same applies to energy, where every kilowatt saved is no different than a kilowatt produced. Therefore, by reducing our energy demands we can curtail bioenergy production and also cut down on the production of other types of energy.

Even though the Global South (Latin America and Africa) has not fully explored land use practices for maximization of its biomass productivity potentials like the Global North (Asia, Europe and North America) (Krausmann et al. 2013), a future increase in biomass supply (induced by land use practice across the Global South) without reduction in consumption outlook, as well as waste reduction and valorization may not lead to the elimination of growing biomass demand deficit occasioned by continued population increase and associated rising food, feed and energy needs, hence the need for reduction in demands, consumption and wastes.

When considering or promoting a certain idea, technology or method, we should be careful to have a clear assessment of the following measures:

1. *Indicators of efficiency* In the case of bioenergy, it can be EROEI. EROEI is a measure of the capacity of an energy source or technology (bioenergy inclusive) to support continuous socioeconomic functions (Hall et al. 2009). It has also been used as an indirect indicator of the kinds of economy or lifestyle an energy source or technology can support, i.e., poor VS. rich economy OR agrarian society/civilization VS. industrial/advanced economy (Lambert et al. 2014). For food production, it can be product per unit energy, water, land used also referred to as the water, land and energy productivity of food production.

Table 1 (continued)

[a] https://www.youtube.com/watch?v=zE6xq1hLhPE, https://www.youtube.com/watch?v=6vQW8Tl_KLc

[b] https://www.youtube.com/watch?v=xv588n0IXrc

[c] China provides several success stories: https://www.youtube.com/watch?v=Sb3vZ1ClPrY, https://www.youtube.com/watch?v=examEbxVSAI, https://www.youtube.com/watch?v=pSn6S-H7m-8. Also in Australia https://www.youtube.com/watch?v=-4OBcRHX1Bc

[d] https://www.youtube.com/watch?v=wezxNnkcsW8

Table 2 Strategies or technologies for producing, reusing and recycling biomass for energy and chemical production

Strategies (technologies)	Gains and efficiencies	Limiting factors (land, water, energy, soil and nutrients) and impacts	Regional limitations
Anaerobic co-digestion of wet biomass	High energy and material efficiency (Ruffino et al. 2015; Arodudu et al. 2017b). Efficient with a mix of wet waste (Arodudu et al. 2013, 2014). Low carbon and water consumption (Arodudu et al. 2016). High scalability (Banks et al. 2011; Xu et al. 2018)	Low degradability with wood and wood products waste (British Biogen 2006; Zhou and Thomson 2009)	Increased adoption across global regional scales (Arodudu et al. 2017a; SEAI 2017). More efficient for local, small scale generation (Demirbas 2011; Meyer et al. 2015)
Conventional bioenergy (biofuel crops-maize, wheat, rapeseed, sunflower, etc.)	High GHG emissions (Hammond and Li 2016), water and land use footprint (Holmatov et al. 2019) Low energy return on energy invested (EROEI) (van Duren et al. 2015; Arodudu et al. 2017a)	Energy, water, soil, land, nitrogen, phosphorus, climate change (Edenhofer et al. 2011; Murphy et al. 2011)	Dry and warm region more susceptible to higher energy, nutrient (nitrogen and phosphorus) and water use (Gerbens-Leenes et al. 2009; Beringer et al. 2011)
Unconventional bioenergy (organic wastes)—Forest residue/forest wood product waste, wastewater and sewage sludge, crop residue, animal manure, food waste, urban leaf falls, garden waste, algae, etc	Low energy, carbon, water and land use (Arodudu et al. 2013, 2014)	Soil and biodiversity conservation (less material will be available for formation of soil and enhancement of biodiversity) (Wiens et al. 2011, Domke et al. 2015) While the belief is that any form of biomass should be used for bioenergy as a last resort only after fulfilling higher-value applications (Bos-Brouwers et al. 2012), some forms (i.e., algae based biofuels) are undesirable from the EROI (1.1–2) and resource requirements point of view: high water (8–193 m^3/GJ) and land footprint (20–200 m^2/GJ) (Gerbens-Leenes et al. 2014)	Adoption in non-OECD, developing countries (mostly from Global South) are more difficult due to lack of infrastructural facilities (Zhou and Thomson 2009; Arodudu et al. 2017a)
Unconventional bioenergy (energy crop horticulture)—home gardens, flat and gently sloping roofs, window slabs, pots, old plastic containers, walls, balcony spaces, frontage and backyard spaces and passages of residential and commercial buildings, as well as vacant spaces in recreational parks and construction sites	Creation of new carbon sinks and increase in carbon sequestration capacity (Arodudu et al. 2014; Mcdougall et al. 2020). Reduction of GHG emissions and decreasing land use footprint (Kulak et al. 2013; Thornbush 2015)	Soil, indoor/outdoor climate, climate change and technology adopted (Gruda 2012, 2019; Gruda et al. 2019). Some variations in urban gardening such as hydroponics may lead to higher energy consumption (Martinez-Mate et al. 2018) Lesser energy conversion capacity than solar PVs: From the energy output point of view, using land for solar PV installations leads to higher energy storage efficiency than allocating land to photosynthetic (i.e., biomass) systems (Blankenship et al. 2011)	Few cities across global North and South, OECD and non-OECD, advanced and developed countries have demonstrated this NPP (and hence the urban vegetable gardening potential) per unit of land is region specific and ranges from 0 to 3.5 kg dry matter m^{-2} depending on the conditions of the place (Haberl et al.a, 2004) and the growing technology adopted

Table 2 (continued)

Strategies (technologies)	Gains and efficiencies	Limiting factors (land, water, energy, soil and nutrients) and impacts	Regional limitations
Forest management and mechanical fuel load reduction—collecting biomass in managed forest areas by removal of debris and dead biomass	Reduces forest fire risk (MFRC 2012; Mathiesen 2016), can offset the costs of fire prevention	Collection technology, human labor intensive, may impact biodiversity and soil conservation (Domke et al. 2012; Doerr and Santín 2016). Clearing forest floor from debris removes nutrients and alters soil carbon budget (Wei et al. 2011; Piirainen et al. 2015), but can be mitigated if digestate is returned to the soils (another energy cost and disturbance of the forest ecosystem)	Becomes especially important in dry areas, which are becoming dryer due to climate change. May be more appropriate in non-OECD countries because of high manual labor intensity
Reclamation of mining and abandoned industrial sites or disturbed land (e.g., roadsides) for production of energy and chemical raw materials (threat of contamination less important)	Reduction of global land use (Gibbs and Salmon 2015; WAD3-JRC 2018). Increased carbon sequestration and sinks (Weng et al. 2015; Tripathi et al. 2016) Improved soil formation and increase in biodiversity (Hayes 2015; Yu et al. 2019) Reduction of nitrogen needs—most suitable reclamation plants are legumes and therefore fix nitrogen. Temperate species like poplar, willow, etc., and tropical species like gliricidia, leucaena, Guinea grass (tropical switchgrass), etc. (Fuwape and Akindele 1997; Voinov et al. 2015). Suitable native species such as kenaf and vetiver neutralizes contaminants (Babalola et al. 2003; Yang et al. 2013)	Human labor and climate change (Johnson 2006; Malagnoux 2007) Choice of species is important for avoidance of fertilizer inputs, building of organic matter, decontamination of toxins and balancing of soil pH (Truong 1999) May require input of fertilizers and organic matter; decontamination of toxins (Festin et al. 2019)	Mostly in dry and warm, developing (non-OECD) and Global South Countries
Process integration and resource (e.g., space) sharing among onsite energy recovery technologies-phosphate recovery-struvite crystallization, thermal leaching or precipitation; biocrude production- hydrothermal liquefaction, pyrolysis; pellet production-hydrothermal liquefaction, pyrolysis, torrefaction, combustion and gasification; bio-coal production-hydrothermal carbonization	Increased resource (material and energy) efficiency (Biller et al. 2017; Smith et al. 2018) Small- and medium-scale implementations are therefore advised (Arodudu et al. 2016, 2017a Expected reduced carbon, water, land use and biodiversity impacts from avoided extraction and transportation of new biomass resources (EC 2015; Smith et al. 2018)	On large scale, processes require large capital and operational costs while the output products may not be compatible with the existing energy infrastructure (Karatzos et al. 2014)	Implementation will be a huge challenge in less developed (non-OECD) countries without the necessary institutional and infrastructural framework

Table 2 (continued)

Strategies (technologies)	Gains and efficiencies	Limiting factors (land, water, energy, soil and nutrients) and impacts	Regional limitations
Mobile energy recovery technologies—pyrolyzers, torrefactors, gasifiers, combustors, combined heat and power generators, etc.	Cheaper to build and operate, and can fit with existing infrastructures, thereby enhancing resource (material and energy) and cost efficiency (James 2014; EBTP 2016) Expected reduced carbon, water, land use and biodiversity impacts from avoided transportation of new biomass resources (Palma et al. 2011; Boateng et al. 2019)	Gasification, pyrolysis, torrefaction and combustion often require energy intensive pre-treatment (grinding, drying) as well as pressure control, and high temperature input, because the organic matter thermally decomposes at around 350–850° C and the operating parameters effect the end products' (oil, gas, char) relative proportions (Jahirul et al. 2012). Requires electricity input to run numerous electric motors while the output product requires deoxygenation (Jahirul et al. 2012) and can be corrosive (Demirbas et al. 2009)	Implementation will be a huge challenge in less developed (non-OECD) countries without the necessary institutional and infrastructural framework

Fig. 2 Iconic Sydney Central Park multifunctional building, which boasts many smart living features (https://www.wsp.com/en-AU/projects/central-park)

2. *Environmental footprints and life cycle impacts* Environmental Footprint Assessment (EFA) and Life Cycle Assessment (LCA) approaches cover areas such as water use, land use and the GHG emissions. Although LCA covers all of these areas (Rebitzer et al. 2004), in EFA, different environmental indicators are developed to focus on a specific resource (Vanham et al. 2019). In general, the EFA and LCA are complementary, follow a life cycle approach (Boulay et al. 2013; Hoekstra 2017; Pfister et al. 2017) and yet have different foci, goals (Hoekstra 2017) and means of communication of the results (Pfister et al. 2017). In LCA, the life cycle inventory analysis (LCI) translates water use, land use or GHG emissions into environmental impacts and their interpretation based on weighting of impacts (Pfister et al. 2017), while the EFA quantifies resource uses, assesses efficiency and security of resource use (Hoekstra 2017). In this respect, the concept of limited resources is the fundamental assumption of the EFA; however, the life cycle impact assessments do not take this into account (Castellani and Sala 2012; Pfister et al. 2017) and rather focuses on comparative assessment of impacts of products (Hoekstra 2017). As such, the two approaches can fill different gaps, i.e., LCA can be used for comparing environmental impacts of different technologies while the EFA can be used to assess their appropriation of limited resources.
3. *Social acceptance and impacts* Here, we need to consider various social indicators, such as employment, equity, education, human health and technology transfer. After all, it is the social dimension that matters most. There are numerous indicators of social well-being, such as happiness index (Helliwell et al. 2018), well-being (OECD 2020), life satisfaction (Ortiz-Ospina and Roser 2017) and others. We do want to make sure that implementation of new technologies and methods of biomass extraction and processing will contribute to the overall

societal well-being and should test the impact of these technologies on various factors that contribute to the relevant indicators. Life cycle sustainability assessment (LCSA) tries to merge both EFA and LCA to address environmental and resource impact, as well as social, policy, health, economic and even cultural concerns within the same framework (Ekener et al. 2018). LCSA will also engender and incorporate stakeholder concerns in every context like other sustainability assessment frameworks (Arodudu et al. 2017).

Conclusions

Can we say that there is enough biomass to meet food, feed, energy and chemical production demands, as well as provide for biological processes under a decarbonized circular economy? We certainly will run out of resources if population and consumption continue to grow. Since a 100% circular economy is not possible in reality, there is a need to reduce global consumption outlook for biomass, even though there are ways that we can increase efficiency and benefit more from what we can extract from photosynthetic assimilation of the energy of the Sun. This will help to stay within the earth's carrying capacity and planetary boundaries as humanity charts its course ahead.

Biomass use should be prioritized for food, then feed, materials and lastly bioenergy (Bos-Brouwers et al. 2012; Piotrowski et al. 2015). The reason being that the value of biomass for food and feed is higher than for materials and bioenergy (Bos-Brouwers et al. 2012) as there are more efficient substitutes (i.e., wind and solar technologies) for energy from biomass, but no alternatives for some biomass derived materials like fat, carbohydrates and proteins (Piotrowski et al. 2015). However, food production process can be improved in many ways, and there is no reason why biomass that is left behind in these processes (i.e., wastes and residue) cannot be used for other purposes. There are also vast tracts of land which are not suitable for food production, where again we can collect biomass for bioenergy or chemical production.

In 2011, the global biomass demand (12.14 Gt dry matter) was already higher than the new global biomass harvested (11.39) (Piotrowski et al. 2015) and is expected to continue to increase in the future (Bos-Brouwers et al. 2012; Piotrowski et al. 2015). Concurrent societal challenges, such as population growth, climate change, biodiversity loss, depletion of mineral resources and water scarcity, may require solutions that further limit biomass supply. For instance, a Global Deal for Nature (GDN) calls for expanding protected areas on the Earth's surface from a current target of 14.9% (terrestrial and inland waters) to 30% (terrestrial and inland waters) by 2030 (Dinerstein et al. 2019) whereby limiting availability of land for biomass growth.

In conclusion, even though we admit that there are strategies for advancing further production and use of biomass under a decarbonized circular economy, in many cases the jury is still out and we can therefore not come to a solid verdict about its future.

Availability of data and material All information used were properly referenced and cited.

References

Aide TM, Clark ML, Grau HR, López-Carr D, Levy MA, Redo D, Bonilla-Moheno M, Riner G, Andrade-Núñezand MJ, Muñiz M (2013) Deforestation and Reforestation of Latin America and the Caribbean (2001–2010). Biotropica 45(2):262–271

Alexander P, Brown C, Arneth A, Finnigan J, Rounsevell MDA (2016) Human appropriation of land for food: The role of diet. Global Environmental Change 41:88–98. https://doi.org/10.1016/j.gloenvcha.2016.09.005

Allen VG, Pond KR, Saker KE, Fontenot JP, Bagley CP, Ivy RL, Evans RR, Schmidt RE, Fike JH, Zhang X, Ayad JY, Brown CP, Miller MF, Montgomery JL, Mahan J, Wester DB, Melton C (2001) Tasco: Influence of a brown seaweed on antioxidants in forages and livestock-A review. J Anim Sci 79:21–31

Altieri MA, Nicholls CI (2008) Scaling up agroecological approaches for food sovereignty in Latin America. Development 51:472–480

Altieri MA, Nicholls CI, Henao A, Lana MA (2015) Agroecology and the design of climate change-resilient farming systems. Agron Sustain Dev 35:869–889

Ames Laboratory (2010). Wind turbines may benefit crops. Ames Laboratory, Ames, Iowa, United States. Retrieved 12 March 2020. Available at https://phys.org/news/2010–12-turbines-benefit-crops.html

Arodudu O, Helming K, Wiggering H, Voinov A (2016) Bioenergy from Low-Intensity Agricultural Systems: An Energy Efficiency Analysis. Energies 10(1):29. https://doi.org/10.3390/en10010029

Arodudu O, van Voinov A, Duren I (2013) Assessing bioenergy potential in rural areas—a NEG-EROEI approach. Biomass Bioenerg 58:350–364

Arodudu O, Ibrahim E, Voinov A, van Duren I (2014) Exploring bioenergy potentials of built-up areas based on NEG-EROEI indicators. Ecol Ind 47:67–79

Arodudu OH, HelmingVoinov KA, Wiggering H (2017a) Integrating agronomic factors into energy efficiency assessment of agro-bioenergy production: acase study of ethanol and biogas production from maize feedstock. Appl Energy 198:426–439

Arodudu O, Helming K, Wiggering H, Voinov A (2017b) Towards a more holistic sustainability assessment framework for agro-bioenergy systems—a review. Environ Impact Assess Rev 62:61–75

Asche F (2015) Aquaculture: Opportunities and Challenges. Retrieved from https://www.ictsd.org/sites/default/files/research/E15_Fisheries_Asche_FINAL.pdf

Avantium (2020) https://www.avantium.com/our-company/; https://www.boredpanda.com/plant-based-coca-cola-carlsberg-bottles-degrade-in-a-year/

Babalola O, Jimba JC, Maduakolam O, Dada OA (2003) Use of vetiver grass for soil and water conservation in Nigeria. Proceedings of Third International Conference on vetiver and Exhibition, pp 293–309. Guangzhou, China, October 2003

Bailey M, Sumaila UR (2015) Destructive fishing and fisheries enforcement in eastern Indonesia. Marine Ecology Progress Series, 530, 195–211. Retrieved from https://www.int-res.com/abstracts/meps/v530/p195–211/

Bais-Moleman AL, Schulp CJE, Verburg PH (2019) Assessing the environmental impacts of production- and consumption-side measures in sustainable agriculture intensification in the European Union. Geoderma 338(15):555–567

Banks C, Chesshire M, Heaven S, Arnold R (2011) Anaerobic digestion of source- segregated domestic food waste: performance assessment by mass and energy balance. Bioresour Technol 102:612–620

Bang C, Vitina A, Gregg JS, Lindboe HH (2013) Analysis of biomass prices: Future Danish prices for straw, wood chips and wood pellets "final report". Retrieved from https://ens.dk/sites/ens.dk/files/Analyser/analysis_of_biomass_prices_2013.06.18_-_final_report.pdf

Barona E, Ramankutty N, Hyman G, Coomes O (2010) The role of pasture and soybean in deforestation of the Brazilian Amazon. Environ Res Lett 5(2):1–9

Barron-Gafford GA, Pavao-Zuckerman MA, Minor RL, Sutter LF, Barnett-Moreno I, Blackett DT, Thompson M, Dimond K, Gerlak AK, Nabhan GP, Macknick JE (2019) Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. Nature Sustain 2:848–855

Baum S, Weih M, Busch G, Kroiher F, Bolte A (2009) The impact of short rotation coppice plantations on phytodiversity. Landbauforschung Volkenrode 59(3):163–170

Beckman J, Xiarchos IM (2013) Why are Californian farmers adopting more (and larger) renewable energy operations? Renew Energy 55:322–330

Bensabeh N, Moreno A, Roig A, Rahimzadeh M, Rahimi K, Ronda JC, Cádiz V, Galià M, Percec V, Cesar Rodriguez-Emmenegger C, Lligadas G (2020) Photoinduced Upgrading of Lactic Acid-Based Solvents to Block Copolymer Surfactants. ACS Sustainable Chemistry and Engineering 8(2):1276–1284. https://doi.org/10.1021/acssuschemeng.9b06599

Beringer T, Lucht W, Schaphoff S (2011) Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy 3(4):299–312. https://doi.org/10.1111/j.1757-1707.2010.01088.x

Biller P, Lawson D, Madsen RB, Becker J, Iversen BB, Glasius M (2017) Assessment of agricultural crops and natural vegetation in Scotland for energy production by anaerobic digestion and hydrothermal liquefaction. Biomass Conversion and Biorefinery 7(4):467–477. https://doi.org/10.1007/s13399-016-0230-x

Blankenship RE, Tiede DM, Barber J, Brudvig GW, Fleming G, Ghirardi M, Gunner MR, Junge W, Kramer DM, Melis A, Moore TA, Moser CC, Nocera DG, Nozik AJ, Ort DR, Parson WW, Prince RC, Sayre RT (2011) Comparing Photosynthetic and Photovoltaic Efficiencies and Recognizing the Potential for Improvement. Science 332(6031):805–809. https://doi.org/10.1126/science.1200165

Błuszkowska U, Nurek T (2014) Effect of mechanization level on manpower needs in forestry. Folia Forestalia Polonica, Series A 56(4):194–201. https://doi.org/10.2478/ffp-2014-0022

Boateng AA, Schaffer MA, Mullen CA, Goldberg NM (2019) Mobile demonstration unit for fast- and catalytic pyrolysis: The combustion reduction integrated pyrolysis system (CRIPS). J Anal Appl Pyrol 137:185–194

Borucke M, Moore D, Cranston G, Gracey K, Iha K, Larson J, Lazarus E, Morales JC, Wackernagel M, Galli A (2013) Accounting for demand and supply of the biosphere's regenerative capacity: The National Footprint Accounts' underlying methodology and framework. Ecol Ind 24:518–533. https://doi.org/10.1016/j.ecolind.2012.08.005

Bos-Brouwers HEJ, Langelaan HC, Sanders JPM, Dijk MV, Vuuren AMV (2012) Chances for biomass: integrated valorisation of biomass resources. Retrieved from Wageningen: https://edepot.wur.nl/248864

Boulay A-M, Hoekstra AY, Vionnet S (2013) Complementarities of water-focused life cycle assessment and water footprint assessment. Environ Sci Technol 47(21):11926–11927. https://doi.org/10.1021/es403928f

Boyd CE, Gross A (2000) Water use and conservation for inland aquaculture ponds. Fish Manage Ecol 7:55–63

Boyd CE, McNevin AA, Clay JW, Johnson HM (2005) Certification issues for some common aquaculture species. Rev Fish Sci 13:231–279

Biogen B (2006) Good practice guidelines: anaerobic digestion of farm and food processing residues. United Kingdom, British Biogen, London, England, p 52

Campbell BM, Thornton P, Zougmoré R, Asten P, Lipper L (2014) Sustainable intensification: What is its role in climate smart agriculture? Curr Opin Environ Sustain 8:39–43

Capritto A (2019a) Impossible Burger vs. beef: Which is better for the environment? CNET, October 28, 2019. Available at https://www.cnet.com/health/is-the-impossible-burger-healthier-than-beef/

Capritto A (2019b) Impossible Burger vs beef: Which is healthier? CNET, October 4, 2019. Available at https://www.cnet.com/health/is-the-impossible-burger-healthier-than-beef/

Carrington D (2018) Researchers race to make bioplastics from straw and food waste. The Guardian, July 5, 2018, Retrieved 03 June 2020. Available at https://www.theguardian.com/environment/2018/jul/05/researchers-race-to-make-bioplastics-from-straw-and-food-waste#:~:text=New%2520bioplastics%2520are%2520being%2520made,wood%2520and%2520produce%2520useful%2520chemicals.

Castellani V, Sala S (2012) Ecological Footprint and Life Cycle Assessment in the sustainability assessment of tourism activities. Ecol Ind 16:135–147. https://doi.org/10.1016/j.ecolind.2011.08.002

Ceballos G, Ehrlich PR, Raven PH (2020) Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction. Proc Natl Acad Sci 117:13596–13602. https://doi.org/10.1073/pnas.1922686117

Chapelle A, Menesguen A, Deslous-Paoli J, Souchu P, Mazouni N, Vaques A, Millet B (2000) Modelling nitrogen, primary production and oxygen in a Mediterranean lagoon. Impact of oyster farming and inputs from the watershed. Ecol Model 127:161–181

Chen G, Patel M (2012) Plastics derived from biological sources: present and future: a technical and environmental review. Chem Rev 112(4):2082–2099

Chojnacka K (2008) Using biosorption to enrich the biomass of seaweeds from the Baltic Sea with microelements to produce mineral feed supplement for livestock. Biochem Eng J 39:246–257

Ciccarese L, Pellegrino P, Pettenella D (2014) A new principle of the European Union forest policy: the cascading use of wood products. L'Italia Forestale e Montana, 69 (5): 285–290. http://dx.doi.org/10.4129/ifm.2014.5.01

Corbin R (2019) A Basement Garden. Chapter 3: Growing Fungus in the Basement—On Purpose! https://www.trybackyardfarming.com/basement-garden-growing-fungus-on-purpose/

CU (2010) Study Shows Wind Turbines on Farmlands May Benefit Crops. University of Colorado, Boulder, United States. Retrieved 12 March 2020. Available at https://www.colorado.edu/today/2010/12/16/study-shows-wind-turbines-farmlands-may-benefit-crops

Daioglou V, Stehfest E, Wicke B, Faaij A, van Vuuren DP (2016) Projections of the availability and cost of residues from agriculture and forestry. GCB Bioenergy 8(2):456–470. https://doi.org/10.1111/gcbb.12285

Davies AR, Cretella A, Franck V (2019) Food sharing initiatives and food democracy: practice and policy in three European Cities. Polit Govern 7(4):8–20

Davies A, Evans D (2019) Urban food sharing: Emerging geographies of production, consumption and exchange. Geoforum 99:154–159

Demirbas A (2004) Combustion characteristics of different biomass fuels. Prog Energy Combust Sci 30(2):219–230. https://doi.org/10.1016/j.pecs.2003.10.004

Demirbas MF, Balat M, Balat H (2009) Potential contribution of biomass to the sustainable energy development. Energy Convers Manage 50(7):1746–1760. https://doi.org/10.1016/j.enconman.2009.03.013

Demirbas A (2011) Waste management, waste resource facilities and waste conversion processes. Energy Convers Manage 52(2):1280–1287

Depta L (2018) Global food waste and its environmental impact. Retrieved 12April 2020. Available at https://en.reset.org/knowledge/global-food-waste-and-its-environmental-impact-09122018

Dinerstein E, Vynne C, Sala E, Joshi AR, Fernando S, Lovejoy TE, Mayorga J, Olson D, Asner GP, Baillie JEM, Burgess ND, Burkart K, Noss RF, Zhang YP, Baccini A, Birch T, Hahn N, Joppa LN, Wikramanayake E (2019) A global deal for nature: guiding principles, milestones, and targets. Science Advances, 5(4), eaaw2869. https://doi.org/10.1126/sciadv.aaw2869

Doerr SH, Santín C (2016) Global trends in wildfire and its impacts: perceptions versus realities in a changing world. Philos Trans R Soc Lond B Biol Sci 371(1696):20150345. https://doi.org/10.1098/rstb.2015.0345

Domke GM, Becker DR, D'Amato AW, Ek AR, Woodall CR (2012) Carbon emissions associated with the procurement and utilization of forest harvest residues for energy, northern Minnesota, USA. Biomass Bioenerg 36:141–150

Dougherty B (2019) Regenerative agriculture: the path to healing agroecosystems and feeding the world in the 21st century. A report for nuffield international farming scholars, Nuffield International Project No. 1801, pp.45

Driscoll J, Tyedmers P (2010) Fuel use and greenhouse gas emission implications of fisheries management: the case of the New England Atlantic herring fishery. Marine Policy 34(3):353–359

Dykstra DP (2001) Chapter 2: Reduced Impact Logging: concepts and issues. In: FAO, Applying reduced impact logging to advance sustainable forest management. Retrieved 12 March 2020. Available at https://www.fao.org/docrep/005/ac805e/ac805e04.htm#bm04

EEA (2019) Climate change adaptation in the agriculture sector in Europe. EEA Report No 04/2019, pp 108. Available at https://www.euroseeds.eu/app/uploads/2019/09/Climate-change-adaptation-in-the-agriculture-sector-in-Europe.pdf

EBTP (2016) Bioenergy value chains 4: pyrolysis and torrefaction. Fact Sheet. European Biofuels Technology Platform, Biofuel, Vincennes, France. Retrieved 12 March 2020. Available at https://www.etipbioenergy.eu/images/EIBI-4-torrefaction%2520and%2520pyrolysis.pdf

EC (2015). Closing the loop—an EU action plan for the Circular Economy. European Commission. Brussels, Belgium. Retrieved 12 April 2020. Available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614

Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss, P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlömer S, von Stechow C (2011) IPCC special report on renewable energy sources and climate change mitigation. Prepared by Working Group III of the intergovernmental panel on climate change, Cambridge University Press, Cambridge

EEA (2006) How much bioenergy can Europe produce without harming the environment?. European Environment Agency, Copenhagen

Ekener E, Hansson J, Larsson A, Pecke P (2018) Developing life cycle sustainability assessment methodology by applying values-based sustainability weighting—tested on biomass based and fossil transportation fuels. J Clean Prod 181:337–351

Ellingsen H, Aanondsen SA (2006) Environmental impacts of wild caught cod and farmed salmon: a comparison with chicken. Int J Life Cycle Assess 1(1):60–65

Elzerman JE, Hoek AC, van Boekel MAJS, Luning PA (2011) Consumer acceptance and appropriateness of meat substitutes in a meal context. Food Qual Prefer 22(3):233–240. https://doi.org/10.1016/j.foodqual.2010.10.006

EPI-FAO (2010) Eco-economy indicators-forest cover. forest resources assessment 2010: global tables. Earth Policy Institute of the Food and Agricultural Organization of the United Nations, Rome, Italy.

Erb K-H, Fetzel T, Plutzar C, Kastner T, Lauk C, Niedertscheider M, Körner C, Haberl H (2016) Biomass turnover time in terrestrial ecosystems halved by land use. Nat Geosci 9(9):674–678

Erb K-H, Lauk C, Kastner T, Mayer A, Theurl MC, Haberl H (2016) Exploring the biophysical option space for feeding the world without deforestation. Nat Commun 7:11382. https://doi.org/10.1038/ncomms11382

FAO, IFAD, UNICEF, WFP and WHO (2019). The state of food security and nutrition in the world 2019: safeguarding against economic slowdowns and downturns.

FAO (2018a) The global status of seaweed production, trade and utilization. Retrieved from https://www.fao.org/3/CA1121EN/ca1121en.pdf

FAO (2018b) The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals. Retrieved from https://www.fao.org/3/I9540EN/i9540en.pdf

FAO and UNEP (2020). The State of the World's Forests (2020) Forests, biodiversity and people. Italy, Rome, p 214

FareShare (2017). FareShare FoodCloud celebrate 5 million meals with Tesco. Retrieved 12April 2020. Available at https://fareshare.org.uk/fareshare-foodcloud-celebrate-5-million-meals-with-tesco/

Festin ES, Tigabu M, Chileshe MN, Syampungani S, Odén PC (2019) Progresses in restoration of post-mining landscape in Africa. J Forest Res 30(2):381–396. https://doi.org/10.1007/s11676-018-0621-x

Fuwape JA, Akindele SO (1997) Biomass yield and energy value of some fast-growing multipurpose trees in Nigeria. Biomass Bioenerg 12(2):101–106

Garcia-Vaquero M, Hayes M (2016) Red and green macroalgae for fish and animal feed and human functional food development. Food Reviews International. 32, 15–45. https://doi.org/10.1080/87559129.2015.1041184In, NH (2019). Vegan burgers vs meat burgers: what's healthier? Plant-based patties have more fibre, less cholesterol, dietitian says, but more sodium. South China Morning Post, 31 October 2019, Available at https://www.scmp.com/lifestyle/health-wellness/article/3035728/vegan-burgers-vs-meat-burgers-whats-healthier-plant-based

Gerbens-Leenes W, Hoekstra AY, van der Meer TH (2009) The water footprint of bioenergy. Proc Natl Acad Sci USA 106(25):10219–10223

Gerbens-Leenes PW, Xu L, de Vries GJ, Hoekstra AY (2014) The blue water footprint and land use of biofuels from algae. Water Resour Res 50(11):8549–8563. https://doi.org/10.1002/2014wr015710

Ghosh PK, Mahanta SK, Ram SN (2017) Sources of reactive nitrogen, environmental and climate effects, management options, and policies, chapter 13- Nitrogen Dynamics in Grasslands, The Indian Nitrogen Assessment, pp 187–205

Giampietro M (2019) On the circular bioeconomy and decoupling: implications for sustainable growth. Ecol Econ 162:143–156. https://doi.org/10.1016/j.ecolecon.2019.05.001

Gibbs JH, Salmon KM (2015) Mapping the world's degraded lands. Appl Geogr 57:12–21

Glenn E, Stafford SM, Squires V (1998) On our failure to control desertification: Implications for global change issues, and a research agenda for the future. Environ Sci Policy 1:71–78

Graedel TE, Allwood J, Birat JP, Buchert M, Hagelüken C, Reck BK, Sibley SF, Sonnemann G (2011) What do we know about metal recycling rates? J Ind Ecol 15(3):355–366

Gruda N (2012) Current and future perspective of growing media in Europe. Acta Hort 960:37–43

Gruda N (2019) Increasing sustainability of growing media constituents and stand-alone substrates in soilless culture systems. Agronomy 9:298–322

Gruda N, Bisbis MB, Tanny J (2019) Influence of climate change on protected cultivation: impacts and sustainable adaptation strategies—a review. J Clean Product 225:481–495

Guillen J, Cheilari A, Damalas D, Barbas T (2016) Oil for fish: an energy return on investment analysis of selected European Union fishing fleets. J Ind Ecol 20(1):145–153

Gurian-Sherman D (2019) Can Eating Cows Save the Planet? Food Revolution Network, October 16, 2019. Retrieved 15 June 2020. Available at https://foodrevolution.org/blog/regenerative-agriculture/

Haas W, Krausmann F, Wiedenhofer D, Heinz M (2015) How circular is the global economy? An assessment of material flows, waste production and recycling in the EU and the world in 2005. J Ind Ecol 19(5):765–777

Haberl H, Geissler S (2000) Cascade utilization of biomass: strategies for a more efficient use of a scarce resource. Ecol Eng 16:111–121

Haberl H, Wackernagel M, Krausmann F, Erb K-H, Monfreda C (2004) Ecological footprints and human appropriation of net primary production: a comparison. Land Use Policy 21(3):279–288. https://doi.org/10.1016/j.landusepol.2003.10.008

Haberl H, Erb KH, Krausmann F, Gaube V, Bondeau A, Plutzar C et al (2007) Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. Proc Natl Acad Sci 104(31):12942–12947. https://doi.org/10.1073/pnas.0704243104

Hall CAS, Balogh S, Murphy DJR (2009) What is the Minimum EROI that a Sustainable Society Must Have? Energies 2:25–47. https://doi.org/10.3390/en20100025

Hall CAS, Dale BE, Pimentel D (2011) Seeking to understand the reasons for different energy return on investment (EROI) estimates for biofuels. Sustainability 3(12):2413–2432

Hammond GP, Li B (2016) Environmental and resource burdens associated with world biofuel production out to 2050: footprint components from carbon emissions and land use to waste arisings and water consumption. Global Change Biol Bioenergy 8(5):894–908. https://doi.org/10.1111/gcbb.12300

Hardin G (1968) The tragedy of the commons. Science 162(3859):1243–1248. https://doi.org/10.1126/science.162.3859.1243

Harmsen PFH, Hackmann MM, Bos HL (2014) Green building blocks for bio-based plastics. Biofuels, Bioprod Biorefin 8(3):306–324. https://doi.org/10.1002/bbb.1468

Harvey B, Brais S (2002) Effects of mechanized careful logging on natural regeneration and vegetation competition in the southeastern Canadian boreal forest. Can J Forest Resour 32:653–666

Hayes J (2015) Returning mined land to productivity through reclamation. Cornerstone 3(4):4–9

Helliwell JF, Layard R, Sachs JD (2018) World Happiness Report.

Hernandez RR, Hoffacker MK, Field CB (2014) Land-use efficiency of big solar. Environ Sci Technol 48:1315–1323

Hiloidhari M, Das D, Baruah DC (2014) Bioenergy potential from crop residue biomass in India. Renew Sustain Energy Rev 32:504–512. https://doi.org/10.1016/j.rser.2014.01.025

Hoekstra AY (2017) Water Footprint Assessment in Supply Chains. In: Bouchery Y, Corbett CJ, Fransoo JC, Tan T (eds) Sustainable supply chains: a research-based textbook on operations and strategy. Springer International Publishing, Cham, pp 65–85

Hoffacker MK, Allen MF, Hernandez RR (2017) Land-sparing opportunities for solar energy development in agricultural landscapes: a case study of the great Central Valley, CA, United States. Environ Sci Technol 51:14472–14482

Holmatov B, Hoekstra AY, Krol MS (2019) Land, water and carbon footprints of circular bioenergy production systems. Renew Sustain Energy Rev 111:224–235. https://doi.org/10.1016/j.rser.2019.04.085

Honlah E, Segbefia AY, Appiah DO, Mensah M, Atakora PO, Sabater A (2019) Effects of water hyacinth invasion on the health of the communities, and the education of children along River Tano and Abby-Tano Lagoon in Ghana. Cogent Soc Sci 5(1):1619652

Hüesker F, Moss T, Naumann M (2011) Managing water infrastructures in the berlin-brandenburg region between climate change. Econ Restruct Commer DIE ERDE 142(1–2):187–208

IEA (2017) Delivering sustainable bioenergy. Retrieved from https://www.iea.org/publications/freepublications/publication/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf

IEA (2019) Renewables information: overview. Retrieved from https://iea.blob.core.windows.net/assets/6959bcb0-d298–404c-80e1–2afaa784798e/Renewables_Information_2019_Overview.pdf

Iffland K, Carus M, de Bie F, Diels L, van Haveren J, Willems P, Ravenstijn J, Vink E, Wagemann K (2015) Definition, calculation and comparison of the "Biomass Utilization Efficiencies (BUE)" of various bio-based chemicals, polymers and fuels. Huerth, Germany

Inman M (2010) Planting wind energy on farms may help crops, say Researchers. Retrieved 30 March 2020. Available at https://www.nationalgeographic.com/news/energy/2011/12/111219-wind-turbines-help-crops-on-farms/

Jahirul M, Rasul M, Chowdhury A, Ashwath N (2012) Biofuels production through biomass pyrolysis: a technological review. Energies 5(12): 4952. Retrieved from https://www.mdpi.com/1996–1073/5/12/4952

James JJ (2014) STTR phase 1 final technical report for project entitled "Developing a Mobile Torrefaction Machine". United States, 2014. doi:10.2172/1122819

Johnson PM (2006) Governing global desertification: linking environmental degradation, poverty and participation. Ashgate Publishing. ISBN:978–0–7546–4359–3. https://books.google.com/books?id=da6vhzHEpf0C

Karatzos S, McMillan JD, Saddler, JN (2014) The potential and challenges of drop-in biofuels (T39-T1). Retrieved from https://task39.sites.olt.ubc.ca/files/2014/01/Task-39-Drop-in-Biofuels-Report-FINAL-2-Oct-2014-ecopy.pdf

Kauffman N, Hayes D, Brown R (2011) A life cycle assessment of advanced biofuel production from a hectare of corn. Fuel 90(11):3306–3314. https://doi.org/10.1016/j.fuel.2011.06.031

Klimiuk E, Pokój T, Budzyński W, Dubis B (2010) Theoretical and observed biogas production from plant biomass of different fibre contents. Biores Technol 101(24):9527–9535. https://doi.org/10.1016/j.biortech.2010.06.130

Krausmann F, Gingrich S, Eisenmenger N, Erb K-H, Haberl H, Fischer-Kowalski M (2009) Growth in global materials use, GDP and population during the 20th century. Ecol Econ 68(10):2696–2705

Krausmann F, Erb K-H, Gingrich S, Haberl H, Bondeau A, Gaube V, Lauk C, Plutzar C, Searchinger TD (2013) Global human appropriation of net primary production doubled in the 20th century. Proc Natl Acade Sci USA 110(25):10324–10329

Krausmann F, Wiedenhofer D, Lauk C, Haas W, Tanikawa H, Fishman T, Miatto A, Schandl H, Haberl H (2017) Global socio-economic material stocks rise 23-fold over the 20th century and require half of annual resource use. Proc Natl Acad Sci USA 114(8):1880–1885

Krausmann F, Lauk C, Haas W, Wiedenhofer D (2018) From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. Global Environmental Change 52:131–140

Kröger R, Dunne EJ, Novak J, King KW, McLellan E, Smith DR, Strock J, Boomer K, Tomer M, Noe GB (2013) Downstream approaches to phosphorus management in agricultural landscapes: Regional applicability and use. Sci Total Environ 442:263–274

Kulak M, Graves AR, Chateerton J (2013) Reducing greenhouse gas emissions with urban agriculture: a Life Cycle Assessment perspective. Landscape and Urban Planning 111:68–78, https://doi.org/10.1016/j.landurbplan.2012.11.007Changes in forest floor and mineral soil carbon and nitrogen stocks in a boreal forest after clear-cutting and mechanical site preparation

Lambert JG, Hall CAS, Balogh S, Gupta A, Arnold M (2014) Energy, EROI and quality of life. Energy Policy 64:153–167

Leahy S (2018) 75% of Earth's Land Areas Are Degraded. National Geographic. Retrieved 30 January 2020. Available at https://www.nationalgeographic.com/news/2018/03/ipbes-land-degradation-environmental-damage-report-spd/

Le Noë J, Roux N, Billen G, Gingrich S, Erb K-H, Krausmann F, Thieu V, Silvestre M, Garnier J (2020) The phosphorus legacy offers opportunities for agro-ecological transition (France 1850–2075). Environ Res Lett. https://doi.org/10.1088/1748-9326/ab82cc

Llevot A, Dannecker P-K, von Czapiewski M, Over LC, Söyler Z, Meier MAR (2016) Renewability is not enough: recent advances in the sustainable synthesis of biomass-derived monomers and polymers. Chem A Eur J 22(33):11510–11521. https://doi.org/10.1002/chem.201602068

Lima M, Skutsch M, de Medeiros Costa G (2011) Deforestation and the social impacts of soy for biodiesel: perspectives of farmers in the south Brazilian Amazon. Ecol Soc 16(4):4

Lin BB, Perfecto I, Vandermeer J (2008) Synergies between agricultural intensification and climate change could create surprising vulnerabilities for crops. Bioscience 58(9):847–854

López-Alt JK (2020) How do they make plant-based meat behave like beef? New York Times, March 3, 2020. Available at https://www.nytimes.com/2020/03/03/dining/plant-based-meat-science.html

Macedo MN, DeFries RS, Morton DC, Stickler CM, Galford GL, Shimabukuro YE (2000s) Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. Proc Natl Acad Sci 109(4):1341–1346

Mair C, Stern T (2017) Cascading utilization of wood: a matter of circular economy? Current Forest Rep 3:281–295

Malagnoux M (2007) Arid land forests of the world: global environmental perspectives, Food and Agricultural Organization, Forestry Department. Afforestation and Sustainable Forests as a means to Combat Desertification, 16–19 April 2007, Jerusalem, Israel.

Martinez-Mate MA, Martin-Gorriz B, Martínez-Alvarez V, Soto-García M, Maestre-Valero JF (2018) Hydroponic system and desalinated seawater as an alternative farm-productive proposal in water scarcity areas: energy and greenhouse gas emissions analysis of lettuce production in southeast Spain. J Clean Prod 172:1298–1310. https://doi.org/10.1016/j.jclepro.2017.10.275

Mathiesen K (2016) How forest management helps lay the conditions for wildfires. The Guardian. Retrieved 30 March 2020. Available at https://www.theguardian.com/environment/2016/may/06/how-forest-management-helps-lay-the-conditions-for-wildfires

Mayer A, Haas W, Wiedenhofer D (2017) How countries' resource use history matters for human well-being–an investigation of global patterns in cumulative material flows from 1950 to 2010. Ecol Econ 134:1–10

Mcdougall R, Rader R, Kristiansen P (2020) Urban agriculture could provide 15% of food supply to Sydney, Australia, under expanded land use scenarios. Land Use Policy 94:104554

McEwan A, Marchi E, Spinelli R, Brink M (2020) Past, present and future of industrial plantation forestry and implication on future timber harvesting technology. J For Res 31:339–351

Meyer AKP, Raju CS, Kucheryavskiy SV, Holm-Nielsen JB (2015) The energy balance of utilising meadow grass in Danish biogas production. Resour, Conserv Recycl 104:265–275. https://doi.org/10.1016/j.resconrec.2015.07.019

MFRC (2012). Minnesotssrs. The Minnesota Forest Resources Council, Saint Paul, Minnesota, United States, pp. 590. Retrieved 12 March 2020. Available at https://mn.gov/frc/docs/MFRC_Revised_Forest_Management_Guidelines_(2012).pdf

Shirazi AM, Akram A, Rafiee S, Mousavi Avval SH, Bagheri Kalhor E (2012) An analysis of energy use and relation between energy inputs and yield in tangerine production. Renew Sustain Energy Rev 16(7):4515–4521. https://doi.org/10.1016/j.rser.2012.04.047

Monagail MM, Cornish L, Morrison L, Araújo R, Critchley AT (2017) Sustainable harvesting of wild seaweed resources. Eur J Phycol 52(4):371–390

Mózner Z, Tabi A, Csutora M (2012) Modifying the yield factor based on more efficient use of fertilizer—the environmental impacts of intensive and extensive agricultural practices. Ecol Ind 16:58–66. https://doi.org/10.1016/j.ecolind.2011.06.034

Mulhollem J (2019) Seaweed feed additive cuts livestock methane but poses questions. ScienceDaily. Penn State Retrieved 12 March 2020. Available at www.sciencedaily.com/releases/2019/06/190617164642.htm

Murphy DJ, Hall CAS, Powers B (2011) New perspectives on the energy return on (energy) investment (EROI) of corn ethanol. Environ Dev Sustain 13:179–202

Nattrass L, Biggs C, Bauen A, Parisi C, Rodríguez-Cerezo E, Barbero MG (2016) The EU bio-based industry: results from a survey. Institute for Prospective and Technological Studies, Joint Research Centre, European Commission

Nemecek T, Huguenin-Elie O, Dubois D, Gaillard G, Schaller B, Chervet A (2011) Life cycle assessment of Swiss farming systems: II. Extensive and intensive production. Agric Syst 104(3):233–245. https://doi.org/10.1016/j.agsy.2010.07.007

Newburger E, Lucas A (2019) Beyond Meat uses climate change to market fake meat substitutes. Scientists are cautious. CNBC, September 2, 2019. Available at https://www.cnbc.com/2019/09/02/beyond-meat-uses-climate-change-to-market-fake-meat-substitutes-scientists-are-cautious.html

OECD (2020) How's Life? Measuring Well-being, OECD Publishing, Paris, https://doi.org/10.1787/9870c393-enhttps://www.oecd.org/statistics/measuring-well-being-and-progress.htm

Olafsson E, Johnstone R, Ndaro-Simon GM (1995) Effects of intensive seaweed farming on the neiobenthos in a tropical lagoon. J Exp Mar Biol Ecol 191:101–117

Oldenzie IR, Weber H (2013) Introduction: reconsidering recycling. Contemp Eur Hist 22(3):347–370

Ortiz-Ospina E, Roser M (2017) Happiness and Life Satisfaction. https://ourworldindata.org/happiness-and-life-satisfaction

Osmanski S (2019) What is plant-based meat? Greenmatters. Retrieved 5th May 2020. Available at https://www.greenmatters.com/p/plant-based-meats

Palma MA, Richardson JW, Roberson BE, Riberad LA, Outlaw JE, Munster C (2011) Economic feasibility of a mobile fast pyrolysis system for sustainable bio-crude oil production. Int Food Agribus Manage Rev 14(3):1–16

Parikka M (2004) Global biomass fuel resources. Biomass Bioenerg 27(6):613–620. https://doi.org/10.1016/j.biombioe.2003.07.005

Park H (2020) Could seaweed hold the answer to producing sustainable animal feed? Farmers Guardian. Retrieved 12 March 2020. Available at https://www.fginsight.com/news/news/could-seaweed-hold-the-answer-to-producing-sustainable-animal-feed-101015

Papadopoulou EL, Basnett P, Paul UC, Marras S, Ceseracciu L, Roy I, Athanassiou A (2019) Green composites of poly(3-hydroxybutyrate) containing graphene nanoplatelets with desirable electrical conductivity and oxygen barrier properties. ACS Omega 4(22):19746–19755. https://doi.org/10.1021/acsomega.9b02528

Parker R, Tyedmers P (2012) Uncertainty and natural variability in the ecological footprint of fisheries: a case study of reduction fisheries for meal and oil. Ecol Ind 16:76–83

Pauly D, Zeller D (2016) Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nature Commun 7:10244

Pelletier N, Tyedmers P (2007) Feeding farmed salmon: Is organic better? Aquaculture 272:399–416

Pelletier N, Tyedmers P (2008) Life cycle considerations for improving sustainability assessments in seafood awareness campaigns. Environ Manage 42:918–931

Pelletier N, Tyedmers P (2010) Life cycle assessment of frozen tilapia fillets from Indonesian lake-based and pond-based intensive aquaculture systems. J Ind Ecol 14(3):467–481

Pelletier N, Tyedmers P (2011) An ecological economic critique of the use of market information in life cycle assessment research. J Ind Ecol 15(3):342–354

Pfister S, Boulay A-M, Berger M, Hadjikakou M, Motoshita M, Hess T, Ridoutt B, Weinzettel J, Scherer L, Döll P, Manzardo A, Núñez M, Verones F, Humbert S, Buxmann K, Harding K, Benini L, Oki T, Finkbeiner M, Henderson A (2017) Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) A critique on the water-scarcity weighted water footprint in LCA. Ecol Ind 72:352–359. https://doi.org/10.1016/j.ecolind.2016.07.051

Phillips MJ (1990) Environmental aspects of seaweed culture. FAO/NACA Technical Resource Papers, Regional Workshop on the Culture and Utilization of Seaweeds, vol II. Network of Aquaculture Centers in Asia Pacific, Bangkok, Thailand, pp 27–31

Piirainen S, Finér L, Starr M (2015) Changes in forest floor and mineral soil carbon and nitrogen stocks in a boreal forest after clear-cutting and mechanical site preparation. Eur J Soil Sci 66(4):735–743

Piotrowski S, Carus M, Essel R (2015) Global bioeconomy in the conflict between biomass supply and demand. Retrieved from https://bio-based.eu/?did=29249&vp_edd_act=show_download

Poisson A, Hall CAS (2013) Time series EROI for Canadian oil and gas. Energies 6:5940–5959. https://doi.org/10.3390/en6115940

Poltoraka BJ, Labelle ER, Jaeger D (2018) Soil displacement during ground-based mechanized forest operations using mixed-wood brush mats. Soil Tillage Res 179:96–104

Ragland KW, Aerts DJ, Baker AJ (1991) Properties of wood for combustion analysis. Biores Technol 37(2):161–168. https://doi.org/10.1016/0960-8524(91)90205-X

Rajewski DA, Takle ES, Prueger JH, Doorenbos RK (2016) Toward understanding the physical link between turbines and microclimate impacts from in situ measurements in a large wind farm. J Geophys Res Atmos 121(22):13392–13414

Reboredo F, Pais J (2014) Evolution of forest cover in Portugal: from the miocene to the present. doi: 10.1007/978-3-319-08455-8

Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt WP, Suhh S, Weidema BP, Pennington DW (2004) Life cycle assessment: Part 1: framework, goal and scope definition, inventory analysis, and applications. Environ Int 30(5):701–720. https://doi.org/10.1016/j.envint.2003.11.005

Reinicke C (2019) Beyond Meat costs more than traditional meat, but data show consumers are willing to pay the premium price - for now (BYND). Retrieved from https://markets.businessinsider.com/news/stocks/beyond-meat-sales-are-high-but-so-is-price-2019-7-1028346898

Regeneration International (2019) Why regenerative agriculture. Retrieved 15 June 2020. Available at https://regenerationinternational.org/why-regenerative-agriculture/

Rentizelas AA, Tolis AJ, Tatsiopoulos IP (2009) Logistics issues of biomass: the storage problem and the multi-biomass supply chain. Renew Sustain Energy Rev 13(4):887–894. https://doi.org/10.1016/j.rser.2008.01.003

Rezaei M, Liu B (2017) Food loss and waste in the food supply chain. Reus, International Nut and Dried Fruit Council, pp 26–27

Ritchie H, Roser M (2020) Seafood production. OurWorldInData.org. Retrieved on 23 March 2020. Available at https://ourworldindata.org/seafood-production

Rogner H-H, Aguilera RF, Archer C, Bertani R, Bhattacharya SC, Dusseault MB, Gagnon L, Haberl H, Hoogwijk M, Johnson A, Rogner ML, Wagner H, Yakushev V (2012) Chapter 7—energy resources and potentials. In Global energy assessment - toward a sustainable future (pp 423–512). Cambridge University Press, Cambridge and New York, NY and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Ruffino B, Campo G, Genon G, Lorenzi E, Novarino D, Scibilia G, Zanetti M (2015) Improvement of anaerobic digestion of sewage sludge in a wastewater treatment plant by means of mechanical and thermal pre-treatments: performance, energy and economical assessment. Biores Technol 175:298–308

Rulli MC, Bellomi D, Cazzoli A, De Carolis G, D'Odorico P (2016) The water-land-food nexus of first-generation biofuels. Sci Rep 6:22521. https://doi.org/10.1038/srep22521

Scarlat N, Martinov M, Dallemand J (2010) Assessment of the availability of agricultural crop residues in the European union: potential and limitations for bioenergy use. Waste Manage 30(10):1889–1897. https://doi.org/10.1016/j.wasman.2010.04.016

Schweier J, Becker G (2013) Economics of poplar short rotation coppice plantations on marginal land in Germany. Biomass Bioenerg 59:494–502

SE4ALL (2013) Global tracking framework. Retrieved from https://documents.worldbank.org/curated/en/603241469672143906/pdf/778890GTF0full0report.pdf

SEAI (2017) Assessment of cost and benefits of biogas and biomethane in Ireland. Sustainable Energy Authority of Ireland, Dublin, Ireland, pp.107 Retrieved 12 April 2020. Available at https://www.seai.ie/publications/Assessment-of-Cost-and-Benefits-of-Biogas-and-Biomethane-in-Ireland.pdf

Severson K (2019) Can meat actually save the planet? Huffpost, July 18, 2019. Retrieved 15 June 2020. Available at https://www.huffpost.com/entry/meat-save-planet-regenerative-farming_l_5d261f7ae4b0583e482b0192?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvbS8&guce_referrer_sig=AQAAAJkT9G7xfRPZYdBXsdzyMo8j084i6YZEWBSqMGz3yZXsf1ZjJn5uar2yzXBp6V3f1n54CWmW7_TXBeCkEbbY8loc9pXaJVVXMBBGLLu4cgcexJkN7R19STG5TWCxg7I1lI3e_CV7WCiPAalSzYAwqtmqpupZ3Qe1xXlNZXiwG-lk

Shepon A, Eshel G, Noor E, Milo R (2016) Energy and protein feed-to-food conversion efficiencies in the US and potential food security gains from dietary changes. Environ Res Lett 11(10):105002. https://doi.org/10.1088/1748-9326/11/10/105002

Sims R, Taylor M, Saddler J, Mabee W (2008) From 1st—to 2nd—Generation biofuel technologies: an overview of current industry and RD&D activities. Retrieved from Paris, France

Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC (2007) A bottom-up assessment and review of global bio-energy potentials to 2050. Prog Energy Combust Sci 33:56–106. https://doi.org/10.1016/j.pecs.2006.08.001

Smith P, Haberl H, Popp A, Erb K-H, Lauk C, Harper R, Tubiello FN, de Siqueira Pinto A, Jafari M, Sohi S, Masera O, Böttcher H, Berndes G, Bustamante M, Ahammad H, Clark H, Dong H, Elsiddig EA, Mbow C, Ravindranath NH, Rice CW, Carmenza RA, Romanovskaya A, Sperling F, Herrero M, House JI, Rose S (2013) How much land-based greenhouse gas mitigation can be achieved without compromising food security and environmental goals? Glob Change Biol 19(8):2285–2302

Smith AM, Whittaker C, Shield I, Ross AB (2018) Potential for production of high-quality bio-coal from early harvested Miscanthus by hydrothermal carbonisation. Fuel 220:546–557

Stanimirova R, Arévalo P, Kaufmann RK, Maus V, Lesiv M, Havlík P, Friedl MA (2019) Sensitivity of global pasturelands to climate variation. Earth's Future 7(12):1353–1366. https://doi.org/10.1029/2019EF001316

Tilman D (1999) Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proc Natl Acad Sci USA 96:5995–6000

Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. Proc Natl Acad Sci 108(50):20260–22026

Thomas DSG, Knight M, Wiggs GFS (2005) Remobilization of southern African desert dune systems by twenty-first century global warming. Nature 435:1218–1221

Thornbush M (2015) Urban agriculture in the transition to low carbon cities through urban greening. Environ Sci 2(3):852–867

Tokiwa Y, Calabia BP, Ugwu CU, Aiba S (2009) Biodegradability of plastics. Int J Mole Sci 10(9): 3722–3742. Retrieved from https://www.mdpi.com/1422–0067/10/9/3722

Trainor AM, McDonald RI, Fargione J (2016) Energy sprawl is the largest driver of land use change in United States. PLoS ONE 11:7896–7906

Tripathi N, Singh RS, Hills CD (2016) Soil carbon development in rejuvenated Indian coal mine spoil. Ecol Eng 90:482–490

Sternberg T (2016) Water megaprojects in deserts and drylands. Int J Water Resour Dev 32(2):301–320. https://doi.org/10.1080/07900627.2015.1012660

Truong PN (1999) Vetiver grass technology for land stabilisation, erosion and sediment control in the Asia Pacific region. In: Proceedings of first asia pacific conference on ground and water bioengineering for erosion control and slope stabilisation, pp 72–84 Manila, Philippines, April 1999.

Tugend A (2019) Is the new meal any better than the old meal. New York Times, September 21, 2019. Available at 10.1080/09670262.2017.1365273https://www.nytimes.com/2019/09/21/climate/plant-based-meat.html

Tyedmers P (2000) Salmon and Sustainability: the biophysical cost of producing salmon through the commercial salmon fishery and the intensive salmon culture industry. Doctoral dissertation. University of British Columbia. https://circle.ubc.ca/handle/2429/13201

Tyedmers P (2001) Energy consumed by North Atlantic Fisheries. In ''Fisheries Impacts on North Atlantic Ecosystems: Catch, Effort and National/Regional Datasets'' (D. Zeller, R. Watson, and D. Pauly, Eds.), Fisheries Centre Research Reports 9(3), 12–34

Tyedmers P (2004) Fisheries and energy use. Encycloped Energy 2:683–693

UN (2020) Desertification. Retrieved from https://www.un.org/en/events/desertificationday/desertification.shtml

USEIA (2019) International Energy Outlook 2019 with projections to 2050. Retrieved from https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf

van den Burg SWK, van Duijn AP, Bartelings H, van Krimpen MM, Poelman M (2016) The economic feasibility of seaweed production in the North Sea. Aquacult Econ Manage 20(3):235–252. https://doi.org/10.1080/13657305.2016.1177859

van Duren IC, Voinov A, Arodudu OT, Firrisa MT (2015) Where to produce rapeseed biodiesel and why? Mapping European rapeseed energy efficiency. Renew Energy 74:49–59

Vanham D, Leip A, Galli A, Kastner T, Bruckner M, Uwizeye A, van Dijk K, Ercin E, Dalin C, Brandão M, Bastianoni S, Fang K, Leach A, Chapagain A, Van der Velde M, Sala S, Pant R, Mancini L, Monforti-Ferrario F, Carmona-Garcia G, Marques A, Weiss F, Hoekstra AY (2019) Environmental footprint family to address local to planetary sustainability and deliver on the SDGs. Sci Total Environ 693:133642. https://doi.org/10.1016/j.scitotenv.2019.133642

Voinov A, Arodudu O, van Duren I, Morales J, Qin L (2015) Estimating the potential of roadside vegetation for bioenergy production. J Clean Product 102:213–225

WAD3-JRC (2018) Mining-world atlas of desertification. Joint Research Centre of the European Commission. Retrieved 30 March 2020. Available at https://wad.jrc.ec.europa.eu/mining

Wackernagel M, Rees W (1998) Our ecological footprint: reducing human impact on the earth (Vol. 9): New Society Publishers

Wackernagel M, Onisto L, Bello P, Linares AC, Falfán ISL, Garcıa JM, Guerrero AIS, Guerrero MGS (1999) National natural capital accounting with the ecological footprint concept. Ecol Econ 29(3):375–390

Wang X, Yang Y, Dong Z, Zhang C (2009) Responses of dune activity and desertification in China to global warming in the twenty-first century. Global Planet Change 67:167–185

Wei X, Kimmins JP, Peel K, Steen O (2011) Mass and nutrients in woody debris in harvested and wildfire-killed lodgepole pine forests in the central interior of British Columbia. Can J For Res 27:148–155

Weng YC, Fujiwara T, Houng HJ, Sun CH, Li WY, Kou YW (2015) Management of landfill reclamation with regard to biodiversity preservation, global warming mitigation and landfill mining: experiences from the Asia-Pacific region. J Clean Product 104:364–373

Wiens J, Fargione J, Hill J (2011) Biofuels and biodiversity. Ecol Appl 21:1085–1095

Williams M (2000) Dark ages and dark areas: Global deforestation in the deep past. J Historic Geograp 26:28–46. https://doi.org/10.1006/jhge.1999.0189

Wood MJ, Carling PA, Moffat AJ (2003) Reduced ground disturbance during mechanized forest harvesting on sensitive soils in the UK. Forestry 76(3):345–361

Wong KH, Cheung PCK (2000) Nutritional evaluation of some subtropical red and green seaweeds: Part I—proximate composition, amino acid profiles and some physico-chemical properties. Food Chem 71(4):475–482. https://doi.org/10.1016/S0308-8146(00)00175-8

Worqlul AW, Dile YT, Jeong J, Adimassu Z, Lefore N, Gerik T, Srinivasan R, Clarke N (2019) Effect of climate change on land suitability for surface irrigation and irrigation potential of the shallow groundwater in Ghana. Comput Electron Agric 157:110–125. https://doi.org/10.1016/j.compag.2018.12.040

Wuehlisch G (2011) Evidence for nitrogen-fixation in the salicaceae family. Tree Planters' Notes 54(20):38–41

WWF (2016) Mapping study on cascading use of wood products. WWF Technical Report., pp.60. Worldwide Fund for Nature, Gland, Switzerland. Retrieved 12 April 2020. Available at https://d2ouvy59p0dg6k.cloudfront.net/downloads/wwf_mondi_cascading_use_of_wood_final_web.pdf

Xu F, Li Y, Ge X, Yang L, Li Y (2018) Anaerobic digestion of food waste – Challenges and opportunities. Biores Technol 247:1047–1058

Yan SH, Song W, Guo JY (2017) Advances in management and utilization of invasive water hyacinth (*Eichhornia crassipes*) in aquatic ecosystems: a review. Crit Rev Biotechnol 37(2):218–228

Yang YX, Lu HL, Zhan SS, Deng T, Lin QQ, Wang SZ, Yang XH, Qiu RL (2013) Using Kenaf (Hibiscus Cannabinus) to Reclaim Multi-Metal Contaminated Acidic Soil. Ying Yong Sheng Tai Xue Bao 24(3):832–838 [Article in Chinese]

Yates MR, Claire YB (2013) Life cycle assessments of biodegradable, commercial biopolymers: a critical review. Resour Conserv Recycl 78:54–66. https://doi.org/10.1016/j.resconrec.2013.06.010

Yu F, Wang JM, Bai ZK (2019) Effects of surface coal mining and land reclamation on soil properties: a review. Earth-Sci Rev 17:35–40

Zabel F, Putzenlechner B, Mauser W (2014) Global agricultural land resources: a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions. PLoS ONE 9(12):e114980

Zhang X, Cai X (2011) Climate change impacts on global agricultural land availability. Environ Res Lett 6(1):014014

Zhou A, Thomson E (2009) The development of biofuels in Asia. Appl Energy 86:S11–S20

Zimring CA (2009) Cash for your trash: scrap recycling in America. Rutgers Univ Press, New Brunswick, NJ