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The battle for biomass: A systematic review of food-feed-fuel competition

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ABSTRACT

We review 75 studies on the competition for biomass and production resources such as land, water, labour and capital across food, feed and fuel production. We identified seven factors that are key to the availability and effective use of biomass and production resources. These ranged from ones related to production, such as crop yields to ones related to policy. Many of these factors resulted in trade-offs across different uses of biomass. Studies had different perspectives (e.g. economic, biophysical) on setting priorities for biomass and suggested different solutions to address competition (e.g. marginal lands). To connect these perspectives we suggest a framework that prioritises biomass and production resources for the use of human food before its use as feed or bioenergy.

1. Introduction

Humanity faces the challenge of feeding a growing population and supplying its energy needs without exhausting the biological and physical resources of the planet, as articulated in the Sustainable Development Goals (SDGs) of the United Nations (UN General Assembly, 2015). Achieving food and nutrition security is central to the SDGs. As the global population grows and becomes wealthier, the demand for food, especially animal-source food will increase particularly in developing countries (Alexandratos and Bruinsma, 2012). Increasing demand for animal-source food, moreover, is intrinsically associated with an increasing demand for feed (Thornton, 2010).

Besides food security, clean and renewable energy is also central to the achievement of the SDGs (UN General Assembly, 2015). The European Union (EU), for instance, has launched ambitious goals to incentivise the use of renewable energies. The EU Renewable Energy Directive sets targets to achieve at least 20% of its total energy use with renewables by 2020, and 32% by 2030 (European Parliament and Council, 2009). Biomass is the most common form of renewable energy, and its demand is expected to increase further (IEA, 2017). About 60% of EU renewable energy, for instance, originates from biomass, such as wood and biofuel crops (Scarlat et al., 2019).

A key question is whether we can produce enough biomass to produce all the food, animal feed and bioenergy needed for our future population. The capacity of the planet to produce biomass is limited by its biophysical boundaries (Erb et al., 2016; Smil, 2012) and by socio-economic and policy constraints (European Environmental Agency (EEA), 2017a). The challenge is, therefore, the competition between food, feed and fuel for biomass. About 40% of all global cropland is currently used to produce high quality feeds, some of which are cereals which humans could also consume (Mottet et al., 2017) resulting in feed-food competition. Around 30% of the global cropland dedicated to cereals is used to grow livestock feed. Direct consumption of these cereals by humans is more resource-efficient than consumption of animal-source food produced by animals fed with these cereals (Garnett, 2009; Goodland, 1997). The use of biomass edible for humans or farm animals for bioenergy production further complicates the competition for resources. Currently, about 13% of global cropland is used to produce biofuels and textiles (Poore and Nemecek, 2018).

There seems to be wide agreement that food, feed and fuel production compete intensively for limited resources, such as land, water, labour and capital (Persson, 2013; Rulli et al., 2016). To mitigate this competition for biomass and avoid increasing the pressure on natural resources and ecosystems, strategies are needed to manage the use of biomass more effectively (Garnett et al., 2015; Haberl et al., 2014; Karlberg et al., 2015; Smith et al., 2010).

One strategy to manage biomass more effectively is based on the concept of circularity in agricultural production, as proposed in food systems research (de Boer and Van Ittersum, 2018). This concept aims to reduce food losses and food waste, using biomass for human consumption first and then recycle any by-products back into the system. Livestock here plays an important role as converters of biomass not suitable for human consumption into food (Van Zanten et al., 2016a,b). In policy, various frameworks exist to guide the effective use of biomass. These frameworks differ in values underlying the cascading of biomass, (e.g. the Waste Hierarchy and Moerman's ladder), such as

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economic benefits or resource-use efficiency (e.g. the Value Pyramid or cascading use) (Rood et al., 2017). Such frameworks have been applied to connect bioenergy policies to concepts of circularity or circular economy (European Environmental Agency (EEA), 2018).

Despite this interest in managing biomass more effectively, we argue that a coherent framework that connects the ideas of circularity with the multiple goals for biomass, such as food, feed and bio-energy, is lacking. More importantly, we argue that a coherent discussion of these multiple goals is lacking, and it is important to discuss priorities for these goals. Similarly lacking is the examination of trade-offs when pursuing different goals for biomass and what factors influence these trade-offs. It is important to discuss what the most effective use of biomass is because setting priorities for one biomass use over another depends on different perspectives (Garnett et al., 2015). Some studies had a food perspective and prioritised biomass used for food production, whereas other studies had a bioenergy perspective and prioritised biomass use for bioenergy production. This sometimes resulted in competing claims for the same resource. Making these perspectives explicit is the first step to effective use. Furthermore, these perspectives are inherently limited by biophysical boundaries, especially in the context of increasing pressure on resources.

The aim of this paper, therefore, was to systematically review the state of the art of the use of biomass for food, feed and bioenergy production, and to what extent studies suggest strategies for effective use of biomass. To that aim, we first identified the factors that are key to the availability and effective use of biomass. Second, we mapped the trade-offs and synergies associated with changes in these key factors. Third, we explored whether solutions suggested to meet the increasing demand for biomass will mitigate or increase the competition for biomass and the resources needed for its production. While acknowledging that biomass can be directed to a wide range of uses, we choose to focus on the three main uses of biomass (food, feed, fuel) and exclude biomaterials and biochemicals. We argue that this is because food security and renewable energy are the main challenges facing humanity in the short to medium-term. Finally, the scope of our paper is limited to the implications of European biomass demand in a global context. We finalise by summarising the main research gaps and uncertainties.

2. Material and methods

We applied a systematic review approach (Boland et al., 2014) aiming to provide a complete summary and synthesis of the literature. Our selection, was based on three phases: 1) an identification phase where records were obtained from three scientific databases, 2) a screening and eligibility phase where records were removed based on pre-selected criteria 3) a final inclusion phase where records were read in full to determine eligibility. Once the screening process was complete, final records were coded in a database for a number of variables on methodology (i.e. objective, conclusion, study approach, name of model, method used, and spatial scale), content and outcomes, and solutions recommended. We chose to focus on Europe as the EU is an important global player in the demand for bioenergy (Banse et al., 2011), while simultaneously being dependent on land from outside the EU to feed livestock (de Visser et al., 2014; European Environmental Agency, 2017a,b). The scope of our conclusions is therefore largely applicable to Europe. Further information on our approach is presented in the supplementary material.

3. Results

The final selection included a total of 75 studies. The studies spanned the years 1996–2017, with most studies included in the study being published in 2016 (Fig. 1). The relations most examined in the studies was the one between food and fuel, representing 47% of the studies, followed by the one between all three uses, representing 32% of all the studies. This is not surprising, given the controversy surrounding the competition between food and biofuels sparked by the 2007/2008 world food price crisis (Nebehay, 2007). This controversy brought about a number of studies that explored the effects of biofuel policies around the world on agricultural commodity prices (Persson, 2015). Studies represented in Fig. 1 increasingly make a distinction between food and feed, reflecting greater concern for the role of livestock in food system sustainability. The inclusion of all three uses of biomass started appearing more frequently from 2009 onwards, indicating a shift towards more integrative studies.

Fig. 2 summarises the scale, methodology, biomass source and the competitions addressed by the different studies. Most studies (40%) were conducted at a global level, where Europe was included as a region. Many studies that looked at the competition between food and fuel uses of biomass were conducted at a global level. However, the majority of the studies that looked at all three uses of biomass were conducted at a country level, possibly indicating the higher level of detail required to understand the relationship between all three uses of biomass. The 75 studies encompassed a wide range of methodologies, from economic approaches to more biophysical approaches, reflecting the complexity of the problem and the need for different approaches. Most studies used a biophysical modelling approach.

With regard to competition around 27% of the studies focused on the direct competition for the biomass itself, i.e. the potential of that biomass to be used for another purpose. The majority of the studies (67%), however, focused on the competition for the land needed to produce the biomass and the fact that productive land is becoming a scarce resource. Although many studies employed economic approaches, such as general and partial equilibrium models, few studies looked at the effects of allocation of capital and labour to the production of food, feed or bioenergy. The majority of studies examining the general equilibrium effects were again concerned with direct competition for biomass and land use competition. Studies that included bioenergy mostly focused on 1st generation feedstocks, made up of starch, oil and sugar crops. Studies looking at forest biomass were lacking. This was

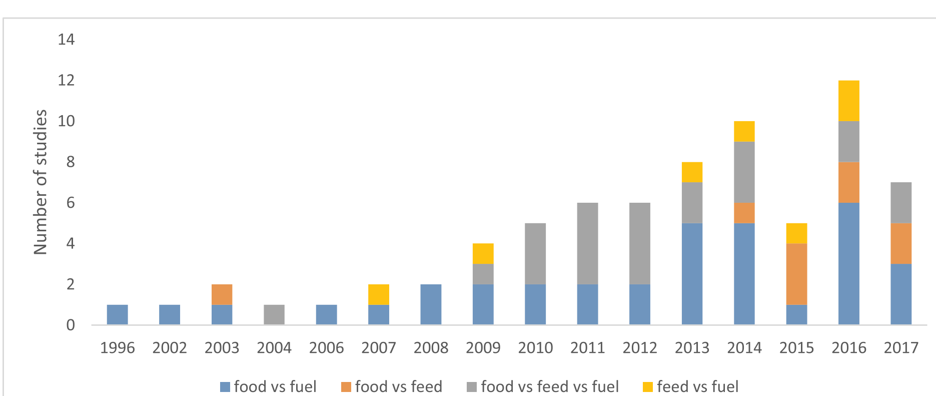

Fig. 1. The number of studies that look at the four relationships across years (1996–2017).

Fig. 2. An overview of the studies reviewed. The numbers represent the number of studies, the total can be greater than 75 because one study can use multiple methodologies, be at different scales etc.

unexpected as around 92% of bioenergy in the EU is generated by forest biomass and is used to generate heat and power, while the remaining 8% comes from agriculture to be used as biofuels in the transport sector (Gurría et al., 2017). One possible explanation is that there is no direct competition for biomass for food, feed and fuel uses, but indirect competition for land. In fact, 45% of studies considered competition for land between food, feed and fuel uses and forest conservation.

The majority of studies considered livestock in their study, especially to account for agricultural land use. Although 81% of all studies included livestock in their analysis, only 41% included information about livestock species and only 28% distinguished different livestock production systems (e.g. landless, grass-based, mixed or broiler chicken, laying hen). The majority (52%) of studies did not consider the effect of trade in their studies. Of those studies that did, 59% said demands for food, feed and fuel will have to be met by trade, with 90% of those saying either food, feed or bioenergy will have to be imported. Around 10% said demand will also indirectly depend on non-domestic water, land, capital or labour.

3.1. Factors that determine the effective use of biomass and associated trade-offs

We identified seven factors that are key to the availability and effective use of biomass (Table 1). A specific factor can increase or reduce the availability of biomass for end-uses and can have positive implications (synergy) or negative implications (trade-off) for resource use or sustainability issues. Sustainability issues identified ranged across all three pillars of sustainability (Fischer et al., 2007), from environmental (e.g. land use, greenhouse gas emissions), economic (increase in food prices, high cost of subsidies) to social (decrease in food availability or energy security). Key factors identified were:

1) Increasing demand for bioenergy (n = 37) has been associated with a number of sustainability issues, from higher food prices (Hertel et al., 2013) to increased water consumption (Damerau et al., 2016). In our review, the increased demand for bioenergy presented many trade-offs between bioenergy, and food and feed production.

The majority of implications reported in Table 1 are trade-offs. For "increased bioenergy demand", for instance, current literature acknowledged 12 potential trade-offs, whereas only four synergies were reported. Increasing bioenergy demand would have negative implications for the use of biophysical resources (e.g. increased land use and land-use change, increased water consumption, increased nitrogen demand, etc.), for socio-economic aspects (e.g. increased food prices and agricultural commodities, higher land rents, increased shadow prices for irrigation water, competition etc.) and for environmental performance (higher greenhouse gas emissions from land-use change, decrease in ecosystem services, such as habitat services, aesthetic values and carbon storage). In contrast, the synergies found were related to the utilisation of co-products from bioenergy production as livestock feed. Other synergies emerged from moving to advanced biofuels, which would decrease competition for land, and ultimately reduce food-feed competition, or eventually even improve ecosystem services. Some of the implications listed for this first factor, however, can be perceived both as trade-off or synergy. For instance, the "need of high rates of technological improvement" was seen as synergy because it could generate new findings and solutions but was seen also as a trade-off because of the need for economic investment or the dependency on technology. Moreover, studies reported some contradictory findings in whether the increased demand for biofuels, whether 1st generation or 2nd generation, would lead to deterioration or improvement of ecosystem services.

2) Increase in crop yields (n = 7). Increasing crop yields on the same amount of agricultural land have been suggested as a strategy to meet the growing demand for biomass while avoiding further agricultural expansion (Godfray et al., 2010).

Some studies found that increasing crop yields met food and feed demands, leaving land available for other uses, such as bioenergy. However, other studies found that even with high yields, land-based bioenergy always hampered food availability. An additional trade-off showed that the advantages of yields can be reversed by climate change and increased competition for biomass.

3) Increase in the use of human-edible ingredients as livestock feed (n = 7). The introduction of high-quality feed in livestock diets has been a common strategy to improve livestock productivity and efficiency (Van Zanten et al., 2018). However, most high-quality feeds are also edible by humans. Hence, this practice can trigger competition for natural resources between feed and food production and impair the contribution of livestock to global food security (Mottet et al., 2017).

Increased number of human-edible components in livestock feed was associated with less food availability and poorer environmental

Table 1
Reported list of trade-offs [T] and synergies [S] organised by the main influencing factors. Citations are all 75 studies included in the review. Further details on the 75 studies are included in the supplementary material.

Influencing Factors	Ref
1. Increased **bioenergy demand** led to: [T] increased land use and consequently higher land rents and higher GHG emissions from land use change [T] loss of forest and pasture converted to arable land [T] increased food prices or agricultural commodity prices [T] reduced food consumption in developing countries [T] increased water consumption and increased shadow prices for irrigation water [T] increased nitrogen demand [T] countries unable to meet bioenergy targets with domestic feedstocks thereby reducing energy security [T] a decrease in ecosystem services, notably food provision, but also habitat services, aesthetic values, and carbon storage [T] less land available for livestock production [T] higher competition for residues/wastes which are of high-value in countries with developed economies [T] intensification of agricultural production towards more high-input production systems (e.g. fertilisers and pesticides) [T] production of bioethanol and biodiesel, which used land and water that competed with food production [S] generation of bioenergy by-products suitable as feed for livestock, which dampened effects of land use and price [S] planting 2nd generation bioenergy, which improved ecosystem services [S] planting 2nd generation bioenergy on non-competitive land, thereby reducing food-fuel competition [S] opportunities for an increase in supply if energy efficiency is increased and energy demand is reduced [S/T] need for high rates of technological improvement [S/T] decreased animal-source food consumption	(Banse et al., 2014; Ben Fradj et al., 2016; Beringer et al., 2011; Bryngelsson and Lindgren, 2013; Burgess et al., 2012; Damerau et al., 2016; Gardebroek et al., 2017; Gissi et al., 2016; Grundmann and Klauss, 2014; Hertel et al., 2013; Hoogwijk et al., 2003; Ignaciuk et al., 2006; Konadu et al., 2015; Lajdova et al., 2016; Langeveld et al., 2014; Larsen et al., 2017; Lotze-Campen et al., 2014, 2010; Lywood et al., 2009; Nonhebel, 2012; Özdemir et al., 2009; Rulli et al., 2016; Russi, 2008; Scarlat et al., 2013; Schmidt et al., 2012; Simon and Wiegmann, 2009; Smeets et al., 2007; Sorda and Banse, 2011; Steubing et al., 2010; Strapasson et al., 2017; Stürmer et al., 2013; Taheripour et al., 2011, 2010; Thrän et al., 2010; Timilsina et al., 2012; Winchester and Ledvina, 2017; Wise et al., 2014)
2. Increased **crop yields** led to: [S] freed up land for bioenergy and reduced food-feed competition However: [T] even with high yields, scenarios with no bioenergy production fed more people [T] yields will be hampered by climate change, increasing competition for land for food, feed, fuel and ecosystem services	(Brinkman et al., 2017; Davis et al., 2014; Erb et al., 2012; Haberl et al., 2011; Hertel et al., 2013; Manceron et al., 2014; Röös et al., 2017)
3. Increase of **human-edible feed** led to: [T] increased food-feed competition However: [S] improved feed conversion ratio in livestock and reduced food-feed competition over time [S] reducing human edible feedstuffs improved environmental performance	(Davis et al., 2014; Ertl et al., 2016, 2015; Mottet et al., 2017; Röös et al., 2017; Schader et al., 2015; Wirsenius, 2003)
4.a. Increased **animal-source food in human diets** led to: [T] limited bioenergy potential because the production resources were used for livestock production 4.b. Decreased **animal-source food in human diets** led to: [T] no land available for crop-based bioenergy when the gap between the highest and lowest calorie diets was closed [S] reduced greenhouse gas (GHG) emissions and reduced land demand [S] more people fed when current uses of food and fuel were assumed and when the gap between the highest and lowest calorie diets was closed	(Davis et al., 2014; Davis and D'Odorico, 2015; Erb et al., 2012; Fazeni and Steinmüller, 2011; Haberl et al., 2011; Röös et al., 2017; Van Kernebeek et al., 2016)
5. Increased **efficiency of food supply chains** led to: [S] freed-up land for bioenergy without displacing other uses [S] reduction of waste of animal-source food and thereby reduced food-feed competition which fed more people [S] efficiency of the food sector combined with utilisation of wastes which increased domestic bioenergy potential	(Brinkman et al., 2017; Davis and D'Odorico, 2015; Röös et al., 2017; Welfle et al., 2014)
6. Type of **bioenergy feedstock** promoted led to: [T] subsidies to promote maize for energy production which resulted in more competition between food and energy sector [T] shifting use of industrial by-products from feed to fuel meant a higher environmental burden across all indicators such as deforestation and land use [S] small biogas plants on farm fed with manure meant synergy between energy and livestock sector [S] use of marginal lands for 2nd generation crops [S] using 2nd generation crops, which increased countries' self-sufficiency rate for bioenergy feedstocks and reduced imports to meet bioenergy demand	(Akgul et al., 2012; Bartoli et al., 2016; Demartini et al., 2016; Nonhebel, 2007, 2004; David Styles et al., 2015; Tonini et al., 2016; Tufvesson et al., 2013; Van Stappen et al., 2016; van Zanten et al., 2016a,b)

(*continued on next page*)

Table 1 (*continued*)

Influencing Factors	Ref
7. Implementation of **Land Use Policies** led to: [T] high sustainability criteria that account for indirect land use change reduced bioenergy potential [T] continued expansion of cropland into nature, even with sustainability criteria [T] high societal cost to incentivise producers to plant only on marginal, less productive land [T] increased food prices and increase water scarcity when climate change mitigation through bioenergy and high forest conservation were coupled [T] constrained future land and limited bioenergy when Land-Use, Land-Use Change and Forestry (LULUCF) strategies based on storing carbon in soil and vegetation were applied [S] land zoning which protected high-value nature land from bioenergy expansion [S] planting on marginal lands which avoided food vs fuel competition [S] more efficient agricultural production when LULUCF strategies were applied [S] high sustainability criteria that accounted for indirect land use change avoided food vs fuel competition	(Beringer et al., 2011; Brinkman et al., 2017; Bryngelsson and Lindgren, 2013; Callesen et al., 2010; Elbersen et al., 2013; Erb et al., 2012; Forsell et al., 2013; Gielen et al., 2002; Gillingham et al., 2008; Hertel et al., 2013; Popp et al., 2011; Treesilvattanakul et al., 2014; Warner et al., 2013)

performance, especially regarding land use Under a number of future scenarios considering different levels of ASF production, decreasing the number of human-edible feedstuffs led to synergies, by not only increasing food availability but also by having improved environmental performance (Röös et al., 2017; Schader et al., 2015).

4) Increase or decrease in the share of animal-source food in the diet (n = 7). The amount of animal-source food in the diet and the livestock production system is key to determine the total amount of food produced and the resources needed for its production (Erb et al., 2016).

Increased animal-source food resulted in a trade-off with bioenergy potential, as production resources such as land were used for livestock production. Decreased animal-source food in human diets brought synergies, such as a reduction in land demand and associated GHG emissions.

5) Increased efficiency of food supply chains (n = 4). Gains in efficiency can be achieved through reduced losses and wastes throughout the chain and/or better integration between food and bioenergy supply chains. Reducing food wastage and food losses along the production chain have been identified as a promising strategy to increase the availability of food, use resources more efficiently and reduce the environmental burden of food production (Scherhaufer et al., 2018; Van Zanten et al., 2014).

"Increased the efficiency of food supply chains" was the only factor showing synergies only and no trade-offs. Reducing losses along the chain resulted in improved food security, enhanced self-sufficiency of food production and reduced land use, which could be eventually used for the bioenergy sector. Furthermore, using co-products of 1st generation biofuel production, such as distiller's dried grains with solubles, and maize stover as animal feed avoided the need to grow more feed and replaced feeds that were competitive with human consumption.

6) Type of feedstocks used for bioenergy (n = 10). The choice of feedstock is an important determinant of the sustainability of bioenergy (Dale et al., 2011). This depends on a number of factors, such as whether the feedstock competes with food or feed production, what was the initial use of the biomass, where and how the feedstock was produced and whether the production of the feedstock and/or its conversion to bioenergy generates valuable co-products.

Studies in this group reported both trade-offs (2) and synergies (3) as resulting effects were highly dependent on the feedstock used and on whether the initial use of the feedstock changed. Trade-offs were related to impacts from changing the initial use of biomass. When crops and by-products used for food and feed were shifted to energy, studies reported a higher environmental burden. However, the use of manure or 2nd generation feedstocks grown on marginal lands provided opportunities not just for improved environmental performance but also for increasing a country's sufficiency on domestic feedstocks.

7) Land-use policies (n = 13). Many land-based policies constrain the management intensity of the land and the total amount of land available for certain uses. For instance, regulations regarding lands for nature conservation, but also the sustainability criteria in the EU Renewable Energy Directive (European Parliament and Council, 2009), climate mitigation activities in the Land Use, Land-Use Change and Forestry (LULUCF) sector or limiting bioenergy to marginal lands.

In relation to the implementation of land-use policies, interventions resulted in synergies (4) as well as trade-offs (5). This may reflect the complexity of the food-feed-fuel competition in itself, the difficulty to design and implement efficient land-use policies with the current body of literature (with sometimes contradictory points of view) and the challenge to foresee all unintended effects (i.e. trade-offs) of any particular intervention.

The different studies analysed were performed at different spatial scales and study areas, used different methodologies, and adopted different assumptions and definitions of concepts (such as the definition of "marginal land"). Moreover, studies had a different starting point, research question or narrative to check. These differences determined the trade-offs and synergies presented. This also led to different solutions for the problem of biomass competition, which may be conflicting across studies. Such important differences between the studies are further explained in the solutions section below and placed in the larger context of scientific literature in the discussion.

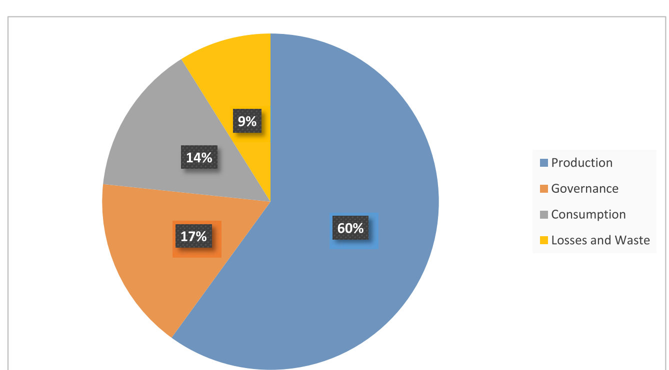

Fig. 3. The shares of recommended solutions.

3.2. Solutions

As a final step in this review, we tracked solutions suggested to avoid food-feed-fuel competition. Around 37% of papers did not recommend a solution. The rest recommended a wide range of solutions. Solutions fell into four categories: production-side solutions, governance solutions, consumption-side solutions and solutions addressing food losses and waste. Most solutions suggested were production-side strategies (Fig. 3).

3.2.1. Production-side solutions

Production-side solutions urged to avoid competition for resources at the production level and often focused on minimising competition between food and bioenergy production. The options to solve the competition between food, feed and fuel reflected a sometimes difficult debate, in which some argue for intensive production whereas others suggest extensive production. For example, many papers considered it important to increase the lifetime productivity of the herd. (e.g. Burgess et al., 2012; Erb et al., 2012; Schader et al., 2015). Other papers, however, suggest to feed livestock on leftovers from arable land (e.g. crop residues, industrial by-products) and grass resources, and avoid the use of human-edible feeds, such as grains, to mitigate competition with food production (e.g. Ertl et al., 2015; Nonhebel, 2004; Özdemir et al., 2009; Schader et al., 2015). The availability of these biomass streams determines the boundary of livestock production and consumption (Van Zanten et al., 2018). These apparently contrasting solutions are based on differences in underlying values and assumptions. The first group argues that to meet the increasing demand for food, and especially animal-source food, we need to produce more with a lower impact on the environment and feed demand whereas the second group argues that livestock can contribute to net food security by converting biomass that is inedible for humans into valuable food. Some studies in both groups suggested that these solutions would reduce overall land-use, thereby leaving room for planting bioenergy crops.

Another option explored to alleviate the competition between food production and bioenergy production was planting bioenergy crops on land not suitable for food production or ‘marginal lands’. However, there is no consensus on the definition and characterisation of marginal lands, which also include grasslands (see further explanation in the discussion section). As such there might be an opportunity cost related to using marginal land for bioenergy production: not all biomass from marginal land can be considered “free” for bioenergy production. So far, however, there appears to be no agreement on the best use of marginal lands (grazing livestock, advanced biofuels or biodiversity conservation), or whether they can be used at all.

3.2.2. Governance solutions

Governance solutions were the second-largest group of recommended solutions after production-side solutions. This shows the importance of addressing the competition for biomass from a policy perspective. The main governance solutions were 1) more equitable trade policies that would allow for better distribution of food (Davis and D'Odorico, 2015). 2) More emphasis on economically viable supply chains and market structures for bioenergy producers (Gissi et al., 2016). 3) Working with local stakeholders for better biomass management (Gissi et al., 2016; Steubing et al., 2010). 4) Being aware of the local context when making decisions about important trade-offs (Grundmann and Klauss, 2014; Van Stappen et al., 2016).

3.2.3. Consumption-side solutions

The impact of livestock production on the environment has received a lot of attention lately (Garnett, 2016; Poore and Nemecek, 2018; Willett et al., 2019) Hence, the most common solution suggested was to decrease the consumption of animal-source food in human diets in high-income countries (e.g. Beringer et al., 2011; Fazeni and Steinmüller, 2011). Besides eating less animal-source food in high income countries, the solution to eat a balanced diet (Davis et al., 2014; Davis and D'Odorico, 2015), i.e. if all people were to consume enough nutrients but not more than they needed, would help to mitigate food-feed-fuel competition and enable feeding more people globally.

3.2.4. Losses and waste solutions

Food loss and food waste are considered to be one of the critical issues affecting the sustainability of the global food system (FAO, 2011). Consequently, reducing food waste is also considered as an important strategy to ease the burden on production resources, such as land and water, to achieve food security and to attain ambitious bioenergy targets (e.g. Brinkman et al., 2017; Burgess et al., 2012; Davis et al., 2014). The emphasis of solutions within this category was to improve resource-use efficiency by combining cascade utilisation principles of biomass, waste management strategies and consumption-side strategies.

4. Discussion

Humanity faces the challenges of feeding a growing population and supplying its energy needs within biophysical boundaries (Haberl et al., 2013). Within a context of greater pressure on resources, meeting these two challenges will require the effective use of biomass (Haberl and Geissler, 2000). This means introducing greater circularity into how we use biomass, setting priorities for its use and making the values underlying these priorities explicit. We argue that a discussion that brings together the multiple goals for biomass is needed. In this paper we argue for ‘effective’ rather than efficient use of biomass following Garnett et al. (2015) to make explicit that directing biomass towards its most ‘high-value’ use is a matter of perspective. Directing biomass towards food may be a priority for one scientific domain while directing biomass towards bioenergy may be a priority for another. Societal values and contexts may also change these priorities. Increasingly the aim of the agricultural system is changing from producing as much food as possible to producing sustainable and nutritious food within the boundaries of the planet (Willett et al., 2019). Future developments may change these priorities, such as the proliferation of bio-based products in response to call for a circular bioeconomy (Zabaniotou, 2018) or future foods, such as cultured meat and insects that may shift diets away from traditional animal-source food (Parodi et al., 2018). We argue that effective use should direct biomass towards food first, and avoid losses and wastes before these are used for feed and/or fuel (de Boer and Van Ittersum, 2018). We do this following Fischer et al's. (2007) ‘hierarchy of considerations’, with biophysical limits representing the ultimate boundary of sustainability. We assessed how the literature takes elements of effective use of biomass into account, particularly acknowledging competition for biomass within biophysical boundaries, suggesting more circular use of biomass and setting priorities for biomass. We looked at the factors that are key determinants of biomass availability and effective use, and looked at the ensuing trade-offs. However, as brought forward in this review, multiple perspectives on how to best use biomass exist. Below, we discuss the research gaps before moving on to our framework that connects these multiple perspectives.

Overall, the number of studies looking at relationships across all three biomass uses shows the state of the art's awareness of the complexity in directing biomass towards its most effective use. Over time, an increasing number of studies considered the inclusion of feed and its complex relationship with food and bioenergy. The key factors influencing biomass use are diverse and related to production (increasing bioenergy, crop yields, use of human-edible feed), consumption (consumption of animal-source food), supply chains (losses and food waste) and policy (promotion of feedstocks and land use policy). A large number of trade-offs shows the scale of the challenge in achieving effective use of biomass. Together, these present the best entry points for intervention for the effective use of biomass. However, while solutions suggested by studies were equally diverse, the overwhelming emphasis remained on the production side. Emphasis should be made on a more systemic approach to effective biomass use that goes beyond tweaking production (Willett et al., 2019).

So far, only a few studies paid attention to the competition for socio-economic resources, i.e. capital and labour, suggesting a gap in research. Only four studies included substitution between capital and labour in their models (Banse et al., 2011; Ignaciuk et al., 2006; Taheripour et al., 2011; Timilsina et al., 2012), but only the study by Ignaciuk et al. (2006) explicitly considered the competition for capital and labour between bioenergy, food and feed production. The most important socio-economic effects of increasing bioenergy production are the potential diversion of capital and labour away from other primary production sectors, such as agriculture (Persson, 2015), hence, impairing food production. Similarly, high levels of subsidies for bioenergy can divert capital from other agricultural sectors and may prove to be an overall social cost. Some studies expect that bioenergy production may displace more labour-intensive production, such as livestock rearing (Trink et al., 2010). The relative labour and capital intensity of a particular bioenergy system will determine whether it generates positive socio-economic effects or whether it displaces other sectors (Persson, 2013). Hence, it is important to better integrate biophysical models which consider environmental limits (i.e. availability of natural resources), with economic models which consider labour and capital (i.e. availability of economic resources). For a fuller picture, the different modelling approaches will need to be integrated to determine what is both environmentally and economically sustainable (Plantinga, 2015). For that, harmonisation and integration of different disciplines is a must, as well as the need to acknowledge that socioeconomic and biophysical limits exist under increased biomass demand.

The role of livestock and their potential to utilise low-opportunity-cost biomass also requires further research. Livestock can convert biomass with low opportunity for direct human consumption (e.g. grass products, crop residues, food processing by-products, and food losses and wastes) into valuable food and manure. Livestock then recycle nutrients into the food system (Garnett et al., 2015), and contribute to net food security. Reducing the amount of food-competitive feedstuffs in animal diets not only increases food security (Davis et al., 2014; Davis and D'Odorico, 2015), but also improves environmental performance in terms of land use (Schader et al., 2015; Van Kernebeek et al., 2016), nitrogen surplus, phosphorus surplus, greenhouse gas (GHG) emissions, non-renewable energy use, freshwater use, pesticide use, deforestation and water-induced soil erosion (Van Zanten et al., 2018). Hence, there will be a need to assess availability, safety and nutritional values of low-opportunity cost biomass as feed for livestock. We need better insights into questions, such as "which animal species or systems are most suitable to upcycle what low-opportunity-cost biomass" (van Hal et al., 2019) and "which biomass streams are most suitable for bioenergy production or for maintaining soil fertility". Although a few studies explored the role of livestock to achieve more sustainable use of biomass, the majority of food-feed-fuel research lacks the detail to explore cascading of biomass use across food, feed and fuel production.

Another research gap was the importance of trade on the competition for resources which poses a challenge for the effective use of biomass. The increasing scarcity of resources can trigger a global rush for the desired resources (e.g. biomass), but also for the resources required for its production (e.g. land, water, nutrients, capital or labour) (Rulli et al., 2012). The EU is dependent on land and water from elsewhere for its domestic production and consumption of food, feed and fuel (Tukker et al., 2014) and in an increasingly interconnected world, this dependency is expected to grow. This dependency on external resources can shift the environmental impact of biomass production to other regions outside the EU. This phenomenon has been described in literature as externalisation, burden-shifting, displacement or leakage effect (Giampietro et al., 2014; Meyfroidt et al., 2010) which can induce effects such as land displacement (Weinzettel et al., 2013), land grabbing (Rulli et al., 2012) and negative impacts on food security and ecosystem services (Naylor et al., 2005; Porkka et al., 2013). This leads to the question at which spatial scale should effective use of biomass be adopted. The answer will largely depend on the priorities we place for biomass and resource use sustainability.

Critical uncertainties about some of the solutions, such as the use of marginal lands and advanced feedstocks remain. Studies from the livestock domain and the bioenergy domain had different perspectives on the aims of the agricultural system and therefore what were the best use of marginal land and of advanced feedstocks.

From the perspective of studies within the livestock domain, marginal lands unsuitable for food crop production ought to be used for livestock production to ease competition with food crop production. Often, this means using them as grazing lands for livestock. While this may reduce the dependency of livestock on arable land, it may still come at the expense of GHG emissions (Garnett et al., 2017). From the perspective of studies within the bioenergy domain, marginal lands are a key solution to growing bioenergy crops without impacting food production. The viability of such a solution depends on the levels of productivity achievable in marginal lands. This remains uncertain since some authors link marginal lands to intrinsic low productivity (Bryngelsson and Lindgren, 2013) others suggest that marginal lands do not necessarily entail low productivity (Gopalakrishnan et al., 2011; Meehan et al., 2017). If marginal lands are defined as ones with low productivity, studies indicated that the solution could prove to be costly to the government or bioenergy consumers. This is because payments would be needed to keep farmers from planting bioenergy on more productive land or limiting the productivity of their land (Bryngelsson and Lindgren, 2013). However, both domains do not consider any other functions these lands may fulfil. For example, there is limited information on the potential natural value of these marginal lands (Immerzeel et al., 2014) and for the social and cultural functions of land which deliver important services for rural people's livelihoods (Rossi and Lambrou, 2008). It should be said that these various claims on marginal lands are not necessarily mutually exclusive. However, to successfully utilise marginal lands it is important to consider their diverse uses to avoid unintended impacts on rural communities, livestock production and nature conservation.

The potential of advanced biofuels to replace conventional biofuels is also uncertain. Many studies cited this is as a way to increase bioenergy without competing with food or feed production. However, currently, the contribution of advanced biofuels to energy production in the EU is marginal. Bioenergy is almost entirely produced from forest biomass or from energy crops in the agricultural sector (Gurría et al., 2017). The little penetration of advanced biofuels can be explained because the technology still lags behind 1st generation biofuels in terms of production, many advanced biofuels are still concepts or pilot studies, there are high costs for implementation and scaling-up, and they face challenges in commercialisation (Bourguignon and Vandenbussche, 2013). The uncertainty in devising which advanced biofuel will develop to a commercial-stage and which production efficiency might attain makes the estimation of its potential at large scale difficult. Defining what is a "second-generation" or "advanced" feedstock is also difficult. For example, the inclusion of "straw" as an advanced feedstock has accrued a debate of the multiple uses straw might have (e.g. as bedding for livestock or return to the soil as organic matter). The use of new second-generation feedstocks will require determining the most sustainable primary use of biomass. The application of biomass cascade principles could provide better management guidance on new feedstocks, such as food wastes (Dahiya et al., 2018). However, there is a need to assess which biomass uses should be prioritised to allow for more effective use.

To connect the various perspectives mentioned above, we propose a framework that connects ideas from food systems research (de Boer and Van Ittersum, 2018; Van Zanten et al., 2018) to broader ideas of circular biomass use (Fig. 4). While biomass can be used for many uses, we consider food security to be the highest priority. From this priority, we propose a number of principles adapted from de Boer and Van Ittersum (2018) First, that biomass should aim for food for humans first. The same principle is applied to the resources needed for biomass production, namely water, land, capital and labour. In other words, these resources should be used for biomass production for food for humans. Second, that by-products, wastes and losses should be avoided then recycled back into the system as food, feed and bioenergy, in that order (de Boer and Van Ittersum, 2018). Third, that livestock can be used to valorise biomass that humans cannot or are not willing to eat. Our framework builds on top of that of de Boer and Van Ittersum (2018) by expanding it from the food system to also include bioenergy. Secondly, we argue that competition does not only refer to competition for biomass or land, but also other production resources such as

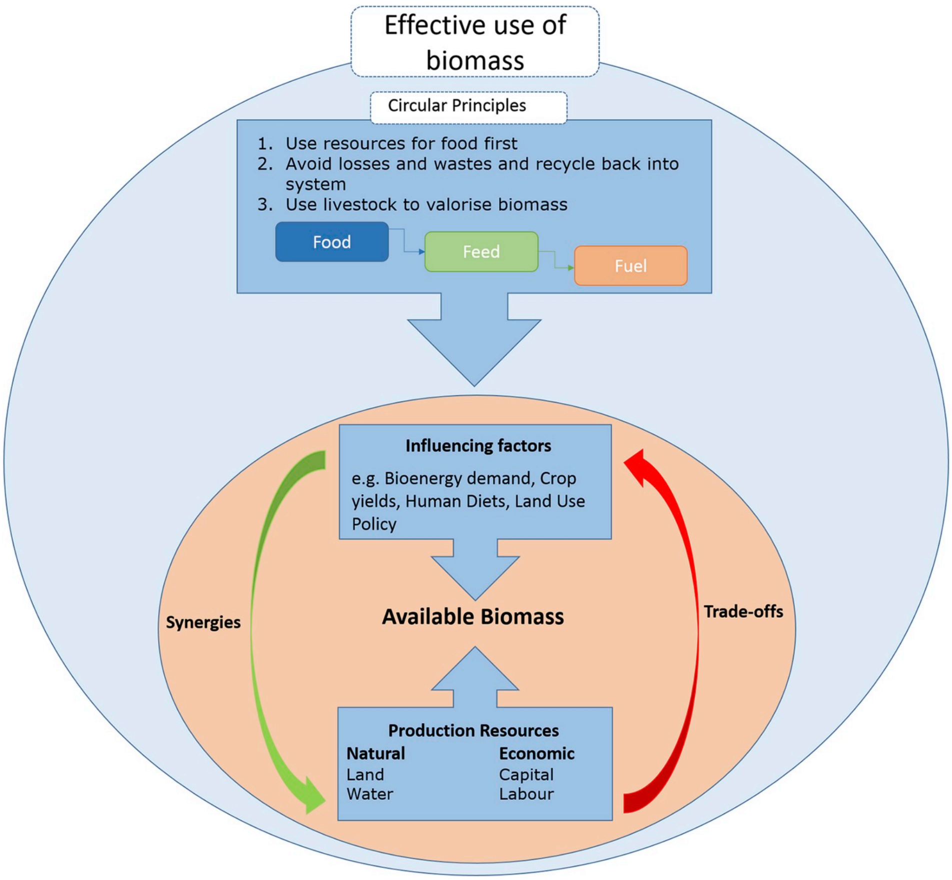

Fig. 4. Presents our framework for effective biomass use. Available biomass is determined by influencing factors, of which we have identified seven from the literature and by production resources. As these resources are limited, there will be trade-offs as well as synergies. Circular principles set limits for biomass for more sustainable resource use, prioritising human consumption of biomass first.

water, capital and labour. Third, as shown in Fig. 4 below, we also expand it by explaining the factors that influence available biomass and create synergies and trade-offs across the goals we want to achieve with that biomass, such as achieving food and bio-energy security etc. These principles of circularity in combination with the production resources define what biomass can be most effectively used for food, feed and fuel.

From a circular perspective, using biomass, land, water, capital and labour for human consumption first will bring a number of benefits. Namely, that livestock will no longer consume large quantities of human-edible food. In a zero human-edible concentrate feed scenario for 2050, Schader et al. (2015)find that greenhouse gas emissions could be reduced by 18%, land occupation by 26% and N-surplus by 46% compared to the reference scenario while still providing sufficient food. This would also free up arable land rendering it available for other purposes such as nature conservation.

Avoiding wastes and recycling by-products can provide equally powerful effects. Davis and D'Odorico (2015) estimate that feed crop calories required to support global consumer waste of animal source food could feed an additional 235 million people.

Finally, using livestock to valorise biomass that humans cannot and will not eat can reduce overall land use, even more than diets with no animal-source food. This is because livestock convert crop residues and by-products from crop production that would otherwise go unused into edible food (Van Kernebeek et al., 2016; Van Zanten et al., 2018).

Many solutions suggested by studies are aligned with our framework, from using livestock to upcycle biomass, avoiding human-edible feedstuffs in feed, reducing consumption of animal-source food, using by-products feedstocks for livestock feed or bioenergy and using marginal lands. However, there is no prioritisation over the best use of biomass and the resources needed for its production between these solutions. Prioritisation is important, particularly in the case of deciding the best use of by-products and co-products of the agro-food industry, which are seen as potential feedstocks for bioenergy. However, many of these feedstocks already have a use as animal feed. For example in the study of Van Zanten et al. (2014), using beet tails as dairy cattle feed instead of a feedstock for anaerobic digestion for the production of on-farm biogas, resulted in a reduction of 239 kg CO2 eq per ton beet tails and a decrease of 154 m^2 land. Similar results were observed with other agro-industrial products, such as oilseed cake and wheat middlings when use was shifted from feed to anaerobic digestion at farm-level (Styles et al., 2015; Tonini et al., 2016; Tufvesson et al., 2013; Van Stappen et al., 2016). This review, therefore, raises awareness of potential feed-fuel competition in the bioeconomy.

An important finding of this review is that food, feed and bioenergy do not just compete for biomass and land but also for water, capital and labour. Therefore, our prioritisation framework should also apply here; this would help bridge perspectives between livestock and bioenergy domains on the best use of marginal land. Furthermore, it would help guide policy to prioritise food and material uses first and energy uses last, avoiding the negative knock-on effects of displacing capital, labour and resources away from food production.

Inevitably relying on sidestream biomasses that do not compete with food production for feed will likely result in lower consumption of animal-source food and lower levels of bioenergy. Studies indicate that livestock fed with only such 'low-opportunity cost feeds' can provide 9–23 g of animal protein per person per day, while the average animal protein supply in Europe stands at around 51 g of animal protein per person per day (Van Zanten et al., 2018). However, this would potentially free up a quarter of global arable land (Van Zanten et al., 2018) besides providing benefits for human health and environment (Willett et al., 2019). 'Food first' estimations of bioenergy potentials using only crop residues and wasted crops show it is possible to produce 491 GL of bioethanol per year (Kim and Dale, 2004), where in 2017 global ethanol production was 127 GL per year (OECD/FAO, 2018). However, such high estimations do not consider other potential uses of this biomass, besides other factors such as climate change and yields (Haberl et al., 2011).

An important question remaining is at which scale should these circularity principles be pursued. From our reviewed studies, 48% argued that domestic biomass would be needed to be supplanted with imports, whether of actual or virtual resources, if food, feed, fuel needs are to be met. So far, research has not provided a clear answer as to at which scale, nutrients cycles should be recycled, and wastes and by-products returned to the system.

In future work, this framework can be expanded in two ways; firstly by including other uses of biomass, such as incorporation into the soil for carbon sequestration, fertilisers, biochemicals and biomaterials. Secondly, the framework can be expanded by including other important functions of land associated with the production of biomass, such as nature conservation. We have so far focused on the three main uses of biomass (food, feed, fuel) because we argue that achieving food security and clean and renewable energy within planetary boundaries remain the main challenges facing humanity in the short to medium-term.

We believe such a framework setting priorities for the effective use of biomass is important because the various uses for biomass are inherently limited by biophysical boundaries, especially in the context of increasing pressure on resources (Fischer et al., 2007). This framework, therefore, argues that biophysical boundaries should be the guiding principles for effective biomass use, which does not necessarily entail directing biomass to its highest economically valuable use. Using such a framework is also useful to trigger new research questions, such as thinking about the availability and best use of biomass by-products that can be reused, the role of livestock in recycling these by-products and the role we give to trade in fulfilling these biomass uses.

5. Conclusion

This review finds that food, feed and fuel do not just compete for limited land but also compete for other resources such as water, labour and capital. The key influencing factors that affect the amount of biomass available for food, feed, fuel purposes related to bioenergy demand, crop yields, amount of human-edible feed fed to livestock, amount of animal source-food in human diets and food supply chain efficiency. Availability of biomass was also particularly affected by which feedstocks policy encouraged to be used for bioenergy and which land-use policies were put in place to discourage food-fuel competition. Important gaps identified in the literature related to the competition or displacement of economic resources when biomass demand is changed, the role of livestock in valorising biomass with low opportunity costs and the role of international trade in the competition for resources.

The reviewed studies had different priorities on how biomass should be directed, for food, feed or bioenergy. These different priorities resulted in contrasting or piecemeal solutions to solve competition for biomass, land and other resources, such as using by-products of the agro-food industry for livestock feed or bioenergy. We set a framework with three principles for the circular use of biomass, using a systems approach and the findings from our review, to help overcome this. By setting priorities directing biomass and the resources needed for its production towards food first, a number of trade-offs across food-feed-fuel uses of biomass can be addressed.

Declaration of competing interest

The authors declare they have no conflicts of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gfs.2019.100330.

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