Bioenergy production and sustainable development: science base for policy-making remains limited

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Bioenergy production and sustainable development: science base for policy-making remains limited

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Abstract

The possibility of using bioenergy as a climate change mitigation measure has sparked a discussion of whether and how bioenergy production contributes to sustainable development. We undertook a systematic review of the scientific literature to illuminate this relationship and found a limited scientific basis for policy-making. Our results indicate that knowledge on the sustainable development impacts of bioenergy production is concentrated in a few well-studied countries, focuses on environmental and economic impacts, and mostly relates to dedicated agricultural biomass plantations. The scope and methodological approaches in studies differ widely and only a small share of the studies sufficiently reports on context and/or baseline conditions, which makes it difficult to get a general understanding of the attribution of impacts. Nevertheless we identified regional patterns of positive or negative impacts for all categories – environmental, economic, institutional, social and technological. In general, economic and technological impacts were more frequently reported as positive, while social and environmental impacts were more frequently reported as negative (with the exception of impacts on direct substitution of GHG emission from fossil fuel). More focused and transparent research is needed to validate these patterns and develop a strong science underpinning for establishing policies and governance agreements that prevent/mitigate negative and promote positive impacts from bioenergy production.

Introduction

During the last decades developed and developing countries have introduced policies to encourage the use of bioenergy including *i.a.* the Brazilian National Alcohol Program (ProAlcool), the US Renewable Fuel Standard (RFS), the EU's Renewable Energy Directive (RED), the Alternative Energy Development Plan (AEDP) in Thailand, and the Indian National Policy on Biofuels (Sorda et al., 2010). The promotion of bioenergy as a climate change mitigation measure has sparked a intensive discussion concerning potential impacts on sustainable development. Commonly mentioned positive impacts focus on opportunities for new uses of land, economic growth, climate change mitigation, increased energy security and employment (Smeets et al., 2007; Nijsen et al., 2012; Mendes Souza et al., 2015). On the other hand, there are concerns about potential disruption to food security and rural livelihoods, direct and indirect greenhouse gas (GHG) emissions from land use change, enhanced water scarcity, ecological impacts, increased rural poverty, and displacement of small-scale farmers, pastoralists and forest users (Dauvergne and Neville, 2010; Delucchi, 2010; German et al., 2011; Gamborg et al., 2014; Hejazi et al., 2015).

How bioenergy interacts with sustainable development has become a key scientific question as demand for bioenergy increases globally. The recent Intergovernmental Panel on Climate Change (IPCC) Working Group III contribution to the Fifth Assessment Report (WGIII AR5) highlights the relationship between context conditions, the use of bioenergy as a mitigation option, and the impacts on sustainable development. Discussing impacts of bioenergy on sustainable development, the IPCC WGIII AR5 concludes that "…*the nature and extent of the impacts of implementing bioenergy depend on the specific system, the development context, and on the size of the intervention*" (Smith et al., 2014).

Different case studies have documented that expanding production of the crops most commonly used to produce bioenergy can affect local incomes, food security, land tenure, or health in positive and negative ways, and that the outcomes of bioenergy production can be unequally distributed (Tilman et al., 2009; Persson, 2014). Model-based assessments have tried to integrate sustainability considerations, pointing out likely interactions between bioenergy and food prices as well as biodiversity and water use(Popp et al., 2011; Lotze-Campen et al., 2014; Scharlemann and Laurence, 2014). However, the effects of bioenergy on livelihoods and the role of governance agreements in promoting or mitigating specific types of impact have not yet been included in modelling exercises (Ackerman et al., 2009; Lubowski and Rose, 2013; Creutzig et al., 2014; Smith et al., 2014). Furthermore, previous studies have concluded that more clarity about the relationships between bioenergy production, livelihoods, and equity is still needed (Hodbod and Tomei, 2013; Creutzig et al., 2013; Hunsberger et al., 2014).

In light of the urgent need for action on climate change (IPCC, 2014), persistent economic and social inequalities, and intensifying competition for land (Lambin and Meyfroidt, 2011; Haberl, 2015), there is a need for science-based policy making with respect to the impacts of bioenergy on sustainable development. We have examined the scientific evidence base for such policy making in a comprehensive systematic review using the scientific literature produced in the time period covered by the IPCC Fifth Assessment Report.

Methodology for reviewing impacts of bioenergy production on sustainable development

The aim of this systematic review was to analyse the state of knowledge about how the production of bioenergy resources affects sustainable development. This is key for understanding to what extent the existent knowledge can provide advice for policy makers. The systematic review focuses on the following impact categories: social, economic, institutional, environmental, and technological (including food security and human health as social). The review is based on the assumption that if production of a bioenergy resource impacts any of the focus categories it also impacts sustainable development. Thus analysing the reported impacts on these focus categories will facilitate an overview of the state of knowledge regarding the impacts from bioenergy production on sustainable development.

We followed the steps included in the methodological guidance for systematic reviews by (Petticrew and Roberts, 2008; Bartolucci and Hillegass, 2010). The review protocol that served as methodological basis included five steps: 1) definition of scope and aims; 2) research questions; 3) search for and selection of evidence; 4) quality appraisal; 5) data extraction and synthesis (see detailed protocol of the systematic review in the supplementary material).

We investigated to what extent the scientific community has answered the following questions which are of high interest in various contexts, including policy, in which decisions on future implementation of bioenergy are decided upon: Where do sustainable development impacts from bioenergy production take place? What is the evidence for the purported impacts? How are impacts attributed and measured? Are there certain context conditions that enable the observed impacts? Are the reported impacts specific to particular biomass resources? These questions were motivated by the discussions addressed in AR5, WGIII (Smith et al., 2014, annex on bioenergy). Although the AR5 considers impacts on sustainable development, it does not provide a geographically differentiated analysis or an understanding of the relation between context conditions and impacts. Several authors (Creutzig et al., 2014; Smith et al., 2014; Bustamante et al., 2014; Stechow et al., 2015) explicitly highlight the need for improving the understanding of regional distribution of mitigation impacts on sustainable development, disaggregating by technologies and bioenergy inputs and under consideration of context conditions. The aim of this article was to make a first step in this direction through a stringent systematic review.

We used the same time frame for scientific publications as the Fifth IPCC Assessment report (AR5) (see supplementary information for the selection criteria and process) and went into a far more detailed analysis with regard to the questions reported above.

The AR5 defines bioenergy as "*energy derived from any form of biomass such as recently living organisms or their metabolic by-products*" (Allwood et al., 2014). We include nine biomass resources in the review: forest residues, unutilized forest growth, dedicated biomass forest plantations, combined forest sources, agriculture residues, dedicated biomass agricultural plantations, organic waste, combined agricultural resources and combined forest and agricultural resources (see protocol in the supplementary information for specific definition of each biomass resource). As the focus of the research was to understand the impacts from production and collection of these biomass resources on development, we did not distinguish the technologies used for producing bioenergy from biomass (i.e. first or second generation) but considered the demand that both technologies can create on biomass resources.

We acknowledge that there is no general agreement on how to measure impacts on sustainable development (Sneddon et al., 2006; Muys, 2013). Thus, we based the systematic review on the development impacts as outlined in the Agriculture, Forestry and Other Land Use (AFOLU) chapter of the IPCC WGIII AR5 (Smith et al., 2014). We considered a set of 33 potential impacts on sustainable development structured into five impact categories: institutional, social and health-related, environmental, economic and technological (see Tables SI3 and SI4). We assumed that if production of a bioenergy resource affects any of these impact categories, it also affects sustainable development. Thus, analysing the reported impacts in a systematic manner provides an overview of the state of knowledge regarding how bioenergy production affects sustainable development as defined above.

Selection of studies and data extraction

The selection process was done in three steps: definition of search criteria, a search in two scientific collections and a quality appraisal. For the search criteria we included thirty inclusion criteria covering all five development categories and two further criteria on bioenergy forms for a set of sixty inclusion criteria combinations; and we included 12 exclusion criteria (see "article selection and data extraction" in the protocol included in the supplementary information for further details). We further refined the selection using 31 categories of Web of Science, including 12 research areas. We limited the search to articles in English. The search was conducted in the Web of Science and in Science Direct including all their data bases. This procedure yielded a wide and inclusive sample of 1175 articles covering all five development categories. For the quality appraisal we randomly selected a subset of articles (n=873 or 74.3% of the original sample), which makes the sub-sample representative. Only 541 of these passed the quality appraisal (criteria and procedure for the appraisal is clarified in the "quality appraisal" section in the protocol included in the supplementary information). 408 articles out of the 541 (75.4%) were randomly included in the data extraction and the research team carefully reviewed all articles. During the data extraction, we removed 92 articles because none of the 33 potential impacts included in our list were discussed, although they did discuss issues belonging to the five categories (that explains why these articles passed the quality appraisal). Thus, the results presented below are based on the analysis of the detailed data extracted from 316 original research articles that discuss at least one of the 33 impacts included.

Data analysis

We analysed the data in three steps: (1) characterization of the study, (2) consideration of the context conditions in the area of the study and (3) reported impacts. Exploratory data analysis revealed a vast heterogeneity of how data were gathered, impacts attributed, and results reported in the 316 analysed articles (see detailed counting of results in the supplementary information, file impacts trees). This heterogeneity combined with the number of variables mostly precluded the use of sophisticated statistical analysis methods, and our analysis is mainly based on descriptive tables and cross-tabulations, combining data from all three steps. The statistical significance of potentially interesting relations between context conditions and impacts was analysed using Fisher-tests (R Core Team, 2014).

Results

Almost half of the articles in the systematic review analyse impacts from dedicated biomass plantations (agriculture and forestry), while few articles examine the sustainable development impacts from using agricultural or forestry residues (4 and 6%, respectively), or organic waste (2.5%) (see Table SI 10). Although several studies report that the use of organic waste as bioenergy feedstock can be associated with positive or low negative impacts, and hence considered an attractive bioenergy resource (Gregg and Smith, 2010; Odlare et al., 2011; Haberl et al., 2011), but the evidence in our review is insufficient to object or support this proposition as too few studies analyse this resource.

Different places, different state of knowledge

Our results show an uneven geographical distribution of the studies, with most articles focusing on developed regions: 26.7% on Europe, and 26.3% on North America; compared to only 13.1% on Asia, 8.2% on Africa, 7.8% on Latin America (Central and South America), 2.2% on Oceania; 15.7% of the studies conduct global analyses (Figure 2, Table SI 11). This distribution contrasts with the share of annual plant biomass production (approximated through Net Primary Production or NPP) of these regions: 16% in Europe, 12% in North America, 19% in Asia, 20% in Africa, 26% in Latin America and 6% in Oceania (Krausmann et al., 2013). Although a multitude of socioeconomic and natural factors influence any region's technical or economic bioenergy potential, we consider NPP a useful proxy for its biophysical suitability for biomass production (Haberl et al., 2013). Modelling and empirical data suggest that current NPP levels may underestimate achievable productivities in human managed systems (DeLucia et al., 2014), but should be viewed in the perspective of scales of cultivation required for bioenergy to make an important contribution to the future energy supply, and also possible ecological impacts of high-input cultivation systems (Haberl, 2016).

Table 1 is divided into three categories of countries: i) well-studied key countries, (section A in Table 1); ii) potentially relevant but understudied countries, i.e., countries with high NPP but few, if any, studies (section B in Table 1); and iii) relatively over-studied countries, i.e., countries with low NPP and hence a relatively minor global contribution to the global bioenergy potential but nevertheless with many studies associated with them (section C in Table 1).

The small share of studies considering impacts on sustainability in developing regions is surprising, as studies assessing global bioenergy potential commonly point to some of the countries in section B as possible large future suppliers of biomass and biofuels (Nijsen et al., 2012; Hoogwijk et al., 2009; Smeets and Faaij, 2010; Beringer et al., 2011; Haberl et al., 2011). For example, in Latin America, only Brazil (contributing 26 cases or 74% to the studies in countries of this region) emerges as a focal point of the scientific literature, while the number of country-specific studies in other countries is small (three studies in Argentina and one study each in Costa Rica, Ecuador, Guatemala, Mexico and Peru). Hence, of the 20 countries in Latin America, only one country with a large NPP is well-studied, whereas six countries are under-studied despite their large potential. Extrapolations of impacts from the local/national to the regional level are thus not yet possible.

When looking at which impacts have been considered and where, our results show that most regions focus on the environmental and economic categories and barely consider social impacts with the exception of food security (see Figure 1 and Table 2). Only studies focusing on Asia and Africa show a more balanced interest across categories.

Only a small number of impacts have been studied across regions

Beyond the impact categories we further analysed which specific impacts were most frequently considered in each region (see Table 3). Studies at the global level focus on impacts on displacement of activities, on deforestation or forest degradation, on soil and water, on food security and on GHG emissions. To a lesser extent, but nevertheless important, global studies look at market opportunities, feedstock prices and technology development and transfer.

The regional distribution of the interest in specific impacts is uneven. In North America (mainly USA) impacts from the environmental category are included among the seven most frequent followed by impacts on prices of feedstock and on market opportunities from the economic category. The three most frequently analysed impacts in Europe and Latin America (mainly Brazil) are those on displacement of activities, on soil and water, and on direct substitution of GHG emissions from fossil fuels. Studies from Oceania only consider six impacts; four of them in the environmental category with the most frequently analysed being impacts on soil and water.

The distribution of analysed impacts in Africa and Asia is more balanced. Most of the impacts have been considered in these two regions, suggesting a better engagement with the complexity of understanding sustainability impacts or an expectation that social impacts are relatively more important in these regions. The five impacts most often considered in Africa are impacts on food security, on energy independence, on economic activity, on employment and on poverty (in this order). In this region, impacts on *land tenure*, on *women* and on *capacity building* are considered more often than in other regions. The five impacts most frequently considered in Asia are those on food security, on economic activity, on soil and water, on displacement of activities and on employment.

Unbalanced understanding about impacts on sustainable development

The perspective of whether impacts are positive, negative or neutral is also uneven across regions. Our analysis of a selection of impacts shows that mostly negative impacts are reported in Latin America and at the global level, while the other regions show a more balanced picture (see Tables

3). The more detailed analysis presented below shows interesting differences in the importance given to each category and on where specific impacts were assessed as positive or negative.

Institutional impacts are included in over 30% of the articles (see Table 2). Within this impact category, *energy independence* is the most frequently studied impact across regions, especially in Europe and Africa, and biofuel deployment is reported mostly as having a positive impact on it. Other impacts in this category such as *cross-sectorial coordination* show mixed results for all regions, while *land tenure* was reported as negatively impacted in Africa, Asia and Latin America.

Social impacts are considered in over 30% of all studies, with *food security* being the most frequently addressed impact in this category (over 25% of the total studies and almost 75% of the articles considering social impacts). We undertook a detailed analysis of food security because it has been mentioned as one major concern for promoting deployment of bioenergy. Negative impacts on food security were reported twice as often as positive impacts. For all regions impacts on food security are reported more often as negative than as positive, except in Africa where an equal number of studies report impacts as positive, negative or neutral (see Figure 2 and Table 3).

In addition, we found that at the global level, the more often models are used for analysing impacts on food security, the higher the frequency of negative impacts (see Figure 2). Although the small number of studies does not provide statistic robustness, this finding suggests a difference in the way impacts on food security are modelled or measured at the global level.

Other key social impacts – including gender and intra-generational impacts, social conflicts, displacement of farmers, and impacts on traditional or indigenous practices – are insufficiently studied in all regions, and practically not considered in global studies.

The environmental impacts category is the most frequently considered category by the studies in the sample (over 70% of the total articles in the review, see Table 2), and each individual impact is addressed by at least a quarter of the studies. Across regions all impacts in this category are reported as mostly negative or neutral, with the exception of *direct substitution of GHG emissions from fossil fuels,* which is considered positive or neutral in all geographical contexts. It is important to note, however, that over 65% of the studies used models for attributing direct substitution of GHG emissions from fossil fuels, and only 20% of these combined models with case study measurements. Thus the qualification of this impact is highly dependent on the system boundaries and attribution criteria used. Negative impacts on the *displacement of activities or other land uses* are more frequently reported in Latin America, North America, Europe, and at the global level (see Table 3). In Asia, slightly more positive impacts are reported compared to other regions.

Impacts on *biodiversity* are predominately reported as negative or neutral (see Table 3), except in a few studies from Europe and North America, whereas impacts on *deforestation or forest degradation* seem to be more negative for Latin America and at the global level. Further, impacts from the *use of fertilizers on soil and water* are reported as negative for Europe, North and Latin America, where these account for the majority of studies addressing this issue.

Economic impacts are considered in over half of all articles (see Table 2), and were predominantly positive for most impacts assessed in this category. Positive effects on *market opportunities* are noticeably reported in studies for North America and Europe (see Table 3), whereas positive effects on *economic activity* were more frequently reported in Africa and Asia. Impacts on *prices of feedstock* show mixed results for all regions. As for other impacts where modelling was used far more often than case study measurements, the positive or negative character of the economic impacts category needs more analysis considering the system boundaries and attribution criteria used.

Over 20% of all articles consider technological impacts (see Table 2). *Technology development and transfer* is the most frequently considered impact, followed distantly by *impacts on labour demand*, *infrastructure coverage and access to infrastructure*. Impacts on technology development and transfer are seen mostly as positive in all regions with only two studies reporting negative impacts: one from Africa and one at the global level (see Table 3).

How context conditions influence development outcomes remains unclear

We analysed how impacts have been attributed by examining whether context conditions were explicitly reported. Context conditions describe the situation in the absence of additional biomass production and use for energy. Insight into these conditions is necessary for establishing a baseline or reference scenario and/or for attributing impacts on sustainable development from bioenergy production in a transparent manner. The systematic review includes 31 possible conditions that can describe the context in relation to the five impact categories (see supplementary information for a complete list of context conditions). We first analysed the extent to which impacts reported in the articles match to the corresponding context conditions at the level of category (i.e., whether context conditions were reported for those categories where impacts were identified).

The analysis shows that only 13.6% of the articles comprehensively describe the context conditions against the category of the reported impacts, whereas 23% do not report context conditions at all. For the remainder, conditions were partially or fully mismatched (i.e., context conditions are described but not for the category of impacts reported). This lack of clarity of the context conditions applies to articles dealing with developed and developing countries, as well as global analyses. However, we found that studies analysing bioenergy production in developing countries report context conditions more often than studies on Europe, North America or those with a global scope (see Figure 3). The lack of information applies across all reported impacts. For instance, from those articles quantifying impacts on food security, only 35% provide context conditions in the corresponding social category; concerning GHG emissions only 12% of articles provide corresponding baseline conditions. We recognize that for some standardized methodologies (e.g., LCA), and for most models, certain assumptions regarding context conditions are embedded in the procedures used. However, when they are not reported and/or validated, which is often the case, it remains unclear how impacts were attributed.

We undertook a deeper analysis of the relationship between context conditions and several specific impacts. Initially, we conducted a descriptive analysis of impacts on food security, which is the most frequently reported social impact, to determine if it is possible to establish the context conditions that trigger positive or negative impacts on food security. 80% of the articles mentioning impacts on food security include some description of the context conditions. We found that in articles reporting impact on food security, most context conditions are considered at least once (see Figure 4) and that no particular context condition clearly stands out in relation to either positive or negative impacts (e.g., conditions that are most frequent in the food security analysis, such as the use of modern technologies, show up both for negative and positive impacts).

The general lack of correlation between context conditions and impact sign is also reflected in the p-values of Fisher-tests, which we applied to all 1023 combinations of context conditions and impacts to check the influence of a particular context condition given or not given on the counts of impact signs. Table 4 displays that only 5 combinations have a p-value below 5% and reports their corresponding numbers of condition-impact combinations.

The Fisher-test indicates if the counts of impact signs in case of condition being "yes" differs significantly from the counts of impact signs when the condition is "no". Thus, a low p-value does not represent strong evidence that the condition has an influence on the impact. This influence can only be postulated if the combination of conditions and impact also suggests its existence and direction. This is the case for only two combinations:

- Combination 1 → context condition " existing deficits in food access and /or food security" and impact on "food security": When the context condition "existing deficits in food access and/or supply" is given, then biomass production for bioenergy is almost exclusively reported to have a negative impact on food security. Studies reporting the absence of these deficits, on the other hand, report either a positive or a neutral impact on food security.
- Combination 2 → context condition "benefit sharing mechanism for economic benefits are in place" and impact on "direct substitution of GHG emissions from fossil fuels": The impact on direct substitution of GHG emissions from fossil fuel is largely positive when no benefit-sharing mechanism for economic benefits are in place, while the presence of such mechanisms exclusively leads to this impact being negative.

For the other three combinations in Table 4, the number of impacts is very small if the condition is answered with "no" and the distribution of impacts (positive, negative or neutral) is ambiguous. Thus, even if the condition being "yes" suggests a positive impact sign in two of these cases, it is not known if these conditions really influence the corresponding impacts.

The regional analysis for the two combinations that in total suggest a correlation between condition and impact are displayed in Table 5. Fisher-tests showed no significant difference between "yes" and "no" answers for any region.

Patterns in the distribution of positive and negative impacts

The results show some general patterns that are worth highlighting (see especially Figures 2, 3 and 4 and Table 3). Impacts on some economic and technological categories are persistently positive across studies and regions. Within these categories impacts on energy independence, direct substitution of GHG emissions from fossil fuels, market opportunities, economic activity and diversification, employment as well as different technological categories are far most often reported as positive. In contrast, most impacts in the social and environmental categories are reported largely as having negative impacts, especially on land tenure, food security, displacement of other activities, biodiversity loss, and conflict and social tension. These patterns indicate an important trade-off: that bioenergy projects may generate positive economic impacts but negative environmental and social impacts.

The incomplete information on context conditions (Figure 3 and statistical analysis) makes it difficult to say anything conclusively across studies on what are the most relevant conditions triggering any specific impact. Yet, previous work has pointed to some reasons worth highlighting, notably that government institutions in countries targeted for bioenergy production often face severe constraints in implementing public policies and regulations intended to protect, for instance, land rights and food security (Ravnborg et al., 2013; Larsen et al., 2014). This is reinforced by our findings on context conditions related to food security and to some extent by the participation of governance related conditions highlighted through the Fisher-Test. It is also worth noting that since climate change mitigation has been an important motivator for promoting bioenergy, it has been a higher research priority than other goals such as those related to biodiversity or land tenure. The latest IPCC Assessment Report made a great advance in including ethics and sustainable development in its considerations and paves the way for a more systemic research approach towards understanding development impacts from bioenergy production. More research is needed in the future to develop this approach, given the knowledge gaps identified in this review.

Conclusions and outlook

Understanding the impacts of bioenergy production on sustainable development has been an important research topic in recent years, but its coverage is uneven, both in terms of geographical coverage, feedstocks considered, and in the categories of impacts considered. Furthermore, results are hardly comparable because context conditions and attribution criteria are not properly reported in the majority of the studies.

In the following we present our conclusions about the research questions in this review.

Where do sustainable development impacts from bioenergy production take place?

Geographically, we identified three distinct groups of countries, based on NPP as a proxy for biophysical biomass production potential, for considering bioenergy deployment in a given country. In the first group we find countries with a high biophysical potential and a reasonable number of studies. These studies give good information about environmental and economic impacts, showing a tendency towards positive impacts from bioenergy production on direct substitution of GHG emissions from fossil fuels, market creation, technology development and transfer. However social, institutional and technological impacts remain uncertain because they were far less often considered. The second group comprises countries with a high NPP but very few studies. Most of these are developing countries where there is a need for better understanding of possible sustainable development impacts of bioenergy implementation. For countries in this group, more research is needed to provide robust information for policy-making and governance agreements. The third group comprises countries with a relatively smaller NPP but many studies. This group consists mainly of developed countries and lessons on methodological issues from these studies can be used for future research in understudied countries.

What is the evidence for the purported impacts and how are impacts attributed and measured?

There is a lack of systematic reporting on criteria for attributing impacts. Despite the existing discussion on attribution of specific methodologies (e.g. Finkbeiner, 2013; Muñoz et al., 2015 on attribution of indirect land use change in LCA), this omission in the studies makes it impossible to pursue a consistent comparison of results. We found that the environmental and economic impact categories were more thoroughly studied whereas far less is known about how bioenergy production will affect the social and institutional categories of sustainable development. Institutional and social impact categories are better considered in country-level studies than in global studies. Although there is an apparent indication of trade-offs between positive impacts on the economic category and negative impacts on the environmental and social categories, more clarity about what triggers the trade-offs could not be achieved due to the non-comparability of the results across the studies (lack of attribution criteria) and to the lack of information on context conditions in the majority of the studies.

Are there certain context conditions that enable the observed impacts?

We found that there is a gap on reporting the specific context conditions prior to any intervention aimed at producing biomass for bioenergy, with less than 15% of the studies providing a comprehensive presentation of the context conditions in the category on which they attributed impacts. The lack of consistency in reporting context conditions and their relation to the reported impacts prevents clear and definitive conclusions on how the context affects the development outcome. Previous assessments have highlighted the need for “good governance” as a condition required for promoting positive impacts of bioenergy production (Creutzig et al., 2014; Smith et al., 2014; Hunsberger et al., 2014). The reported negative impacts on land tenure, food security and food production, or other social and institutional aspects bear witness that bioenergy deployment can result in undesirable consequences and on the importance of understanding the context conditions, especially existing governance of natural resources.

Are the reported impacts specific to particular biomass resources?

We found a concentration of studies dealing with dedicated biomass production, especially agricultural plantations. Other biomass resources have been less studied and the use of waste as bioenergy feedstock has not received much systematic scrutiny. We conclude that analytical frameworks and methods that facilitate the analysis at a higher level of complexity, i.e., including more categories or allowing aggregation from various studies, are still needed. Such frameworks need to ask for the inclusion and reporting of context conditions, explicitly and transparently, so that context-dependent differences can be identified. Future empirical research, especially case studies, should aim to inform about the most effective governance arrangements – and identify situations where governance agreements have insufficient capacity to guarantee that bioenergy deployment consider international due diligence standards.

It is opportune to interpret our results in the context of the recent IPCC assessment of climate change. The IPCC author team concluded that:

> *“One strand of literature highlights that bioenergy could contribute significantly to mitigating global GHG emissions via displacing fossil fuels, better management of natural resources, and possibly by deploying BECCS. Another strand of literature points to abundant risks in the large-scale development of bioenergy mainly from dedicated energy crops and particularly in reducing the land carbon stock, potentially resulting in net increases in GHG emissions” (Smith et al, 2014)*

One interpretation of this divergence is that the first strand of literature emphasizes technological opportunities, such as yield increases, to reduce land use impact, and reap economic opportunities, while the other strand of literature investigates environmental dimensions under risk of being harmed (Creutzig, 2014). The growing literature exploring sustainable landscape management systems for the provision of biomass and other ecosystem services might gradually come to bridge the gap between these two strands of literature. Not the least, the integration of bioenergy systems into agriculture landscapes has been recognized as a promising option for addressing environmental impacts associated with current agriculture systems (Clarke et al., 2014; Edenhofer et al., 2014; Smith et al., 2014).

The IPCC report annex on bioenergy also points out that environmental, social, and economic consequences of bioenergy deployment are site specific, but remains inconclusive on weighting the consequences across case studies. This review goes beyond the IPCC assessment in providing a comprehensive meta-analysis, demonstrating that case studies evaluated so far tend to see increased economic and employment opportunities, GHG savings from fossil fuel displacement, and infrastructure development, but also risks related to land use change, in particular GHG emissions, food security, soil and water quality, biodiversity, and socially problematic outcomes.

Since the publication of the latest IPCC assessment report, further research on bioenergy has been published, which is in line with the main conclusions of our systematic review. The screening of this literature suggests that case studies mostly emphasize GHG emissions metrics and economic performance (e.g. (García et al., 2015; Mandaloufas et al., 2015)) and Dale et al. (2015) point out the importance of appropriate sustainability criteria and indicators. This observation suggests that the systematic bias observed in our survey of case studies can be interpreted as showing that social dimensions have been assigned a lower priority by scientists and policy processes than some environmental and economic dimensions.

There are limitations to the systematic review presented in this article. First, the complexity of the subject of analysis, such as the high number of potential interactions within the system boundaries and the lack of inclusion of criteria for analysing trans-boundary impacts or trade-offs between specific criteria and scale of the impacts, renders results of models and case studies partially inconclusive and subject to a priori values of investigators (Tribe et al., 1976). Second, most results in both cases depend on attributional accounting, which has been argued to be possibly misleading, while consequential accounting, being subject to higher uncertainties, might provide more policy-relevant information. This is especially relevant for studies using LCA methods (Brandao et al., 2013; Hertwich, 2014; Plevin et al., 2014; Plevin et al., 2014). Third, we focused on studies published in English only. These limitations should be considered in future studies, and analysed using complementary assessment methods.

Overall, we find that comparatively assessing the impacts of bioenergy production on sustainable development using the available scientific literature is a considerable challenge, but we are able to propose four recommendations for future research: a) pursue a more stringent use of frameworks and methodologies that attribute impacts of bioenergy production on all development categories; b) report context conditions and criteria for attributing development impacts transparently; c) improve understanding of impacts of bioenergy production in developing countries with potentially favourable biophysical conditions for bioenergy; and d) improve understanding of potential sustainable development impacts in different regions of using other bioenergy feedstock than biomass from dedicated plantations (e.g., organic waste and /or agricultural/forestry residues). Addressing these issues is essential for providing a more solid scientific basis for policy making and governance agreements in the field of bioenergy and sustainable development.

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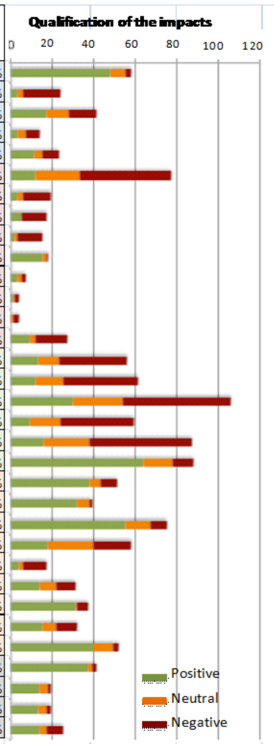
Country	# of studies	% of global NPP	Rank # studies	Rank NPP
A. Countries with more than 1 study and more than 1% of global NPP				
United States	80	6.50%	1	3
Brazil	25	12.10%	2	1
China	13	5.60%	4	5
India	13	2.30%	5	10
Canada	9	6.00%	10	4
Indonesia	9	3.20%	12	8
United Republic of Tanzania	8	1.10%	14	19
Australia	7	4.90%	15	6
B. Countries with less than 5 studies and more than 1% of global NPP				
Russian Federation	3	11.30%	27	2
Argentina	3	2.40%	23	9
Dem. Rep. of the Congo	0	3.70%	98	7
Colombia	0	1.90%	89	11
Peru	1	1.60%	51	12
Angola	0	1.50%	65	13
Mexico	1	1.50%	48	14
Venezuela	0	1.50%	209	15
Bolivia	0	1.40%	78	16
Sudan	0	1.30%	192	17
Kazakhstan	0	1.20%	131	18
C. Countries with 5 or more Studies and less than 1% of global NPP				
Italy	14	0.24%	3	63
Sweden	13	0.36%	6	50
United Kingdom	12	0.23%	7	65
Malaysia	10	0.56%	8	32
South Africa	10	0.63%	9	28
Germany	9	0.37%	11	46
Thailand	9	0.51%	13	35
Mozambique	6	0.91%	16	22
Austria	5	0.08%	17	97
Belgium	5	0.04%	18	125
Spain	5	0.37%	19	48
Denmark	4	0.05%	20	119
France	4	0.58%	21	31
Netherlands	4	0.04%	22	123

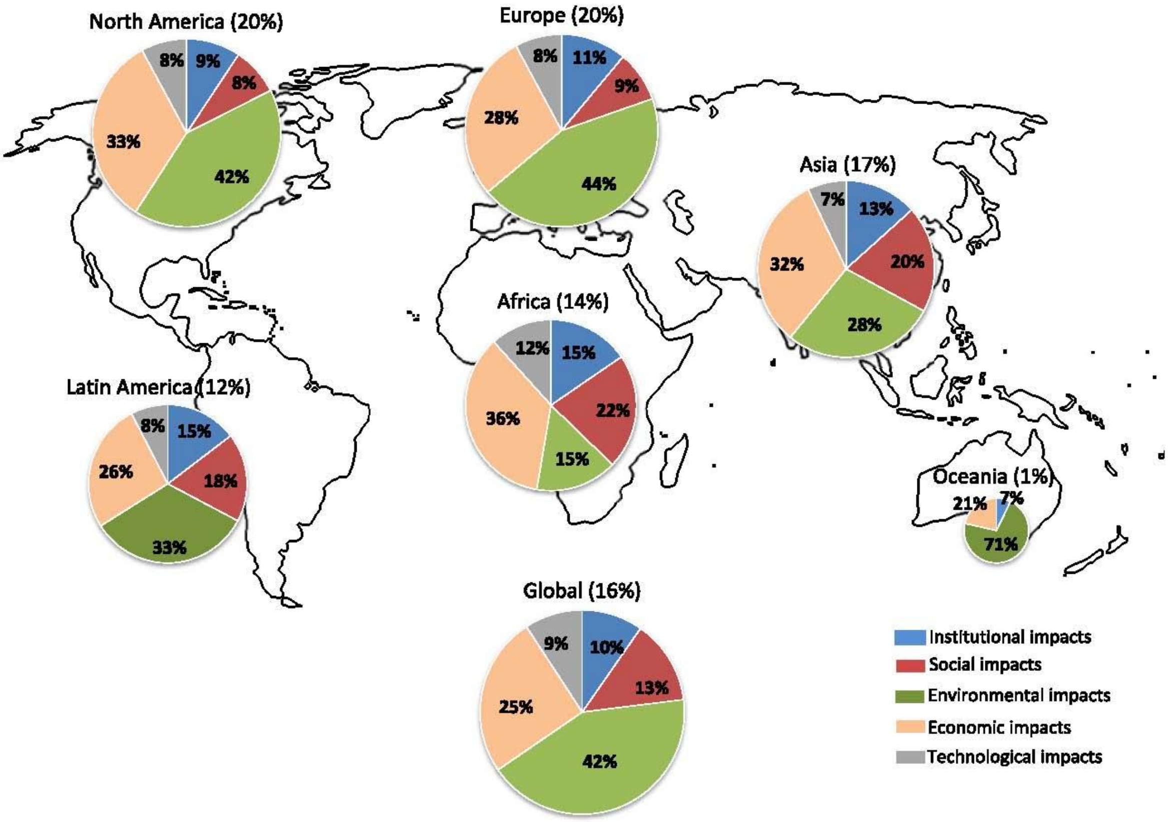
Impact category	No. Studies	Share of category in all studies	Impact on	No. Studies	Share of impact in all studies	Share of impact in the category
Institutional	105	33.23%	Energy independence	59	19%	56.2%
			Land tenure	25	8%	24.8%
			Cross-sectoral coordination(+)/conflicts (-)	41	13%	39.0%
			Labour rights	15	5%	14.3%
			Participative mechanisms	23	7%	21.9%
Social and health	105	33.23%	Food security	81	25.6%	74.3%
			Conflicts or social tension	19	6.0%	17.1%
			Traditional or indigenous practices	17	5.4%	16.2%
			Displacement of farmers	15	4.7%	13.3%
			Capacity building	18	5.7%	16.2%
			Women	7	2.2%	6.7%
			Elderly people	4	1.3%	3.8%
			Specific ethnic groups	4	1.3%	3.8%
			Health impacts	28	8.9%	26.7%
Environmental	222	70.25%	Deforestation or forest degradation	59	18.7%	26.1%
			Use of fertilizers with - impacts on soil and water	63	19.9%	27.9%
			Soil and water	115	36.4%	51.8%
			Biodiversity	64	20.3%	28.8%
			Displacement of activities or land uses	95	30.1%	41.9%
			Direct GHG emission substitution	96	30.4%	43.2%
Economic	165	52.22%	Economic activity	53	16.8%	32.1%
			Economic diversification	44	13.9%	26.1%
			Market opportunities	79	25.0%	47.9%
			Prices of feedstock	63	19.9%	37.0%
			Concentration of income	17	5.4%	10.3%
			Poverty	32	10.1%	18.8%
			Use of waste or residues creates socio-economic benefits	39	12.3%	23.6%
			Mid and long-term revenue's certainty	36	11.4%	21.2%
			Employment	55	17.4%	32.7%
Technological	72	22.78%	Technology development and transfer	44	13.9%	61.1%
			Infrastructure coverage	22	7.0%	30.6%
			Access to infrastructure	22	7.0%	30.6%
			Labour demand	28	8.9%	38.9%

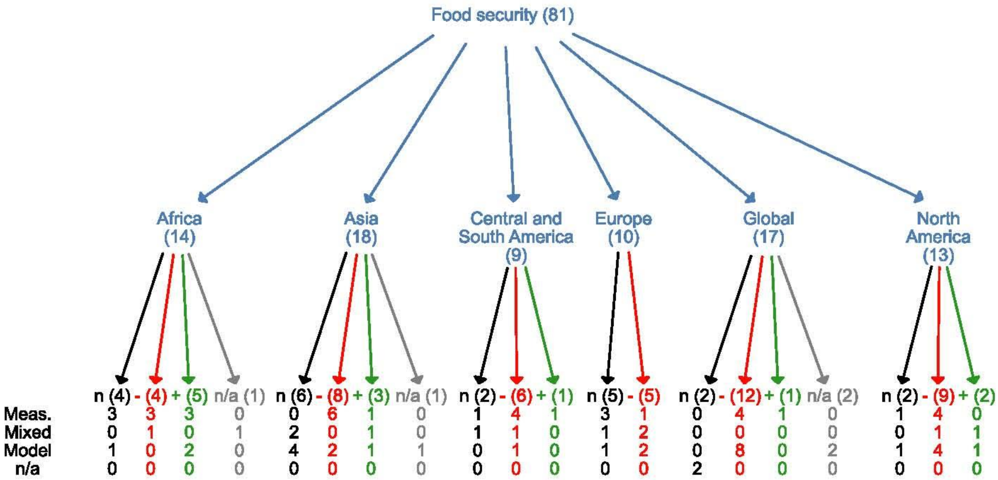


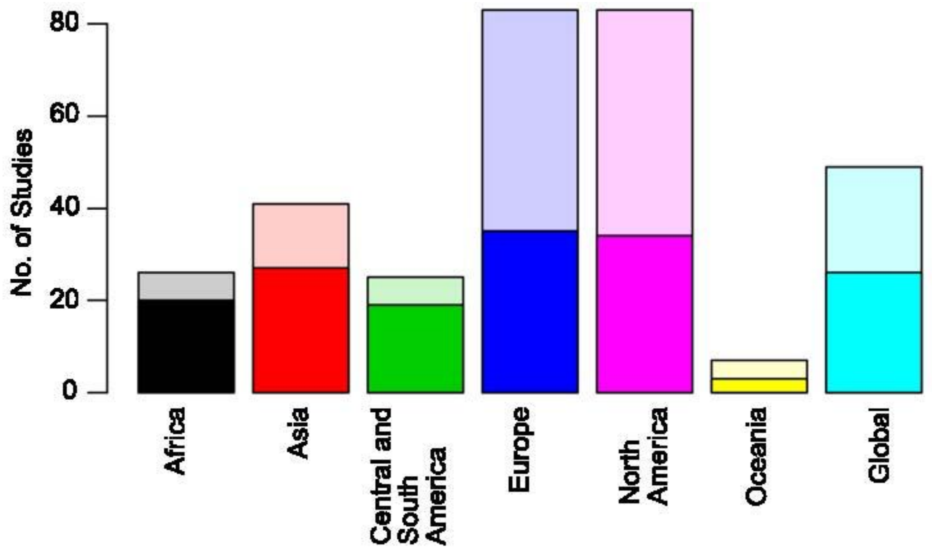
Region / Impacts on	North America +	North America n	North America -	Europe +	Europe n	Europe -	Asia +	Asia n	Asia -	Africa +	Africa n	Africa -	Latin America +	Latin America n	Latin America -	Oceania +	Oceania n	Oceania -	Global +	Global n	Global -	n/a
Energy independency	9	2	0	10	3	1	8	0	0	8	2	1	6	0	0	0	0	0	6	0	1	2
Cross-sectoral coordination	4	1	3	2	1	6	6	2	0	2	0	0	1	2	2	0	1	0	2	4	2	
Land tenure	2	3	0	1	0	1	0	0	6	0	0	7	0	0	4	0	0	0	0	0	1	1
Food security	2	2	9	0	4	5	3	6	8	4	4	4	0	2	6	0	0	0	2	2	11	4
Health impacts	0	1	1	2	0	5	4	1	1	1	0	3	1	0	3	0	0	0	1	1	2	1
Conflicts or social tension	0	1	0	0	0	1	1	0	4	1	1	3	1	1	3	0	0	0	0	0	2	0
Soil and water	7	8	17	10	3	7	7	2	7	2	2	3	1	1	7	2	1	2	1	7	9	9
Direct substitution from GHG emissions	11	4	2	24	4	3	9	1	0	2	1	0	4	2	4	2	0	0	11	2	1	8
Displacement of activities or land uses	3	2	9	3	30	9	6	4	5	0	0	6	2	2	8	0	0	0	2	4	12	8
Biodiversity	3	5	9	5	5	6	1	0	6	0	0	1	0	0	7	0	0	1	0	5	5	5
Deforestation or forest degradation	3	3	4	2	2	4	2	0	4	2	0	4	1	1	6	0	0	0	2	3	11	5
Use of fertilizers with impact on soil & water	4	3	10	4	4	11	3	0	3	1	1	1	0	1	6	0	1	1	0	3	4	2
Market opportunities	18	1	2	15	3	1	5	2	1	3	2	1	5	0	2	1	1	1	8	3	0	4
Prices of feedstock	7	7	7	1	5	4	4	1	1	1	3	2	3	0	0	0	0	0	2	5	4	6
Employment	10	0	1	6	0	0	9	1	0	8	3	1	5	2	1	0	0	0	2	3	0	3
Economic activity	5	0	0	7	2	1	10	1	4	10	0	2	3	0	0	0	0	0	3	2	1	2
Economic diversification	7	1	0	8	2	1	5	1	1	5	1	0	5	0	0	0	0	0	2	1	0	5
Technology development and transfer	5	0	0	8	0	0	5	0	0	5	1	1	6	0	0	0	0	0	8	1	1	3
Labour demand	2	1	2	3	0	0	3	0	0	6	0	2	0	1	3	0	0	0	0	0	0	3
Infrastructure coverage	1	3	1	5	0	0	2	0	0	3	1	0	1	0	0	0	0	0	2	0	0	3

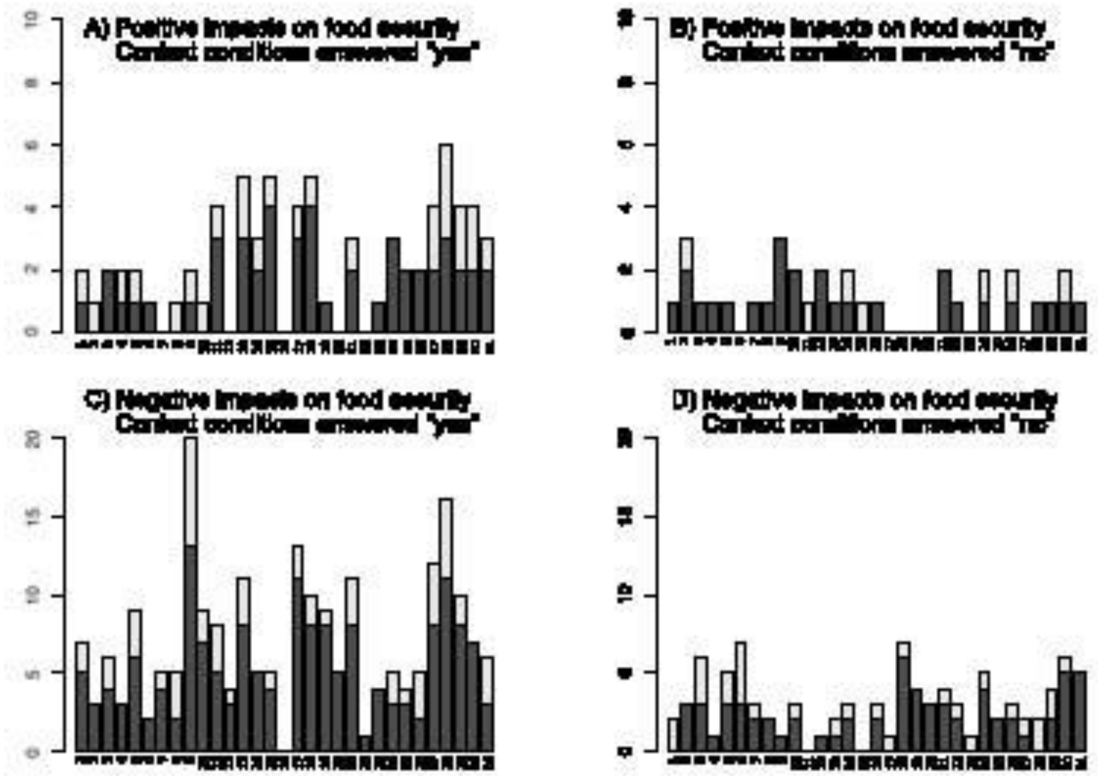
			Combination Condition / Impact					
Impact	Condition	p-value (Fisher-test)	yes / +	yes / -	yes / n	no / +	no / -	no / n
Food security or food production (negative if reduced or positive if improved)	Existing deficit in food access and/or supply	0.00154111	2	20	3	3	1	4
Conflicts or social tension	Existing deficit in food access and/or supply	0.02222222	7	1	2	0	0	1
Direct substitution of GHG emissions reductions from fossil fuels	Sharing mechanisms of economic benefits in place	0.03571429	0	2	0	6	0	0
Prices of feedstock	Modern (industrial) technologies	0.04449388	11	4	13	1	2	0
Employment (being employment creation (+) or employment reduction (-))	Mechanisms for sectorial coordination are in place	0.04545455	7	0	0	2	1	2

Region / Combination	"Existing deficit in Food access" and "Food security"							"Sharing mechanisms in place" and "Direct substitution of GHG emissions reductions"						
	yes / +	yes / -	yes / n	no / +	no / -	no / n	Total	yes / +	yes / -	yes / n	no / +	no / -	no / n	Total
Africa	1	2	2	1	0	0	6	0	0	0	0	0	0	0
Asia	1	6	1	0	0	2	10	0	0	0	2	0	0	2
Europe	0	2	0	0	0	1	3	0	0	0	1	0	0	1
North America	0	4	0	1	1	0	6	0	0	0	2	0	0	2
Oceania	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Latin America	0	1	0	1	0	1	3	0	2	0	0	0	0	2
Global	0	5	0	0	0	0	5	0	0	0	1	0	0	1
Total	2	20	3	3	1	4	33	0	2	0	6	0	0	8


North America (20%)
8%
9%
8%
33%
42%
Europe (20%)
8%
11%
9%
28%
44%
Asia (17%)
7%
13%
32%
20%
28%
Africa (14%)
12%
15%
36%
22%
15%
Latin America (12%)
8%
15%
26%
18%
33%
Oceania (1%)
21%
7%
71%
Global (16%)
9%
10%
13%
25%
42%
Institutional impacts
Social impacts
Environmental impacts
Economic impacts
Technological impacts


Food security (81)
Africa (14)
Asia (18)
Central and South America (9)
Europe (10)
Global (17)
North America (13)
n (4) - (4) + (5) n/a (1)
n (6) - (8) + (3) n/a (1)
n (2) - (6) + (1)
n (5) - (5)
n (2) - (12) + (1) n/a (2)
n (2) - (9) + (2)
Meas. 3 3 3 0 0 6 1 0 1 4 1 3 1 0 4 1 0 1 4 0
Mixed 0 1 0 1 2 0 1 0 1 1 0 1 2 0 0 0 0 0 1 1
Model 1 0 2 0 4 2 1 1 0 1 0 1 2 0 8 0 2 1 4 1
n/a 0 0 0 0 0 0 0 0 0 0 0 0 0 2 0 0 0 0 0 0


No. of Studies
0
20
40
60
80
Africa
Asia
Central and South America
Europe
North America
Oceania
Global


A) Positive impacts on food security
Context conditions answered "yes"
B) Positive impacts on food security
Context conditions answered "no"
C) Negative impacts on food security
Context conditions answered "yes"
D) Negative impacts on food security
Context conditions answered "no"