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Brinkman, Marnix L. J.; Wicke, Birka; Faaij, Andre P. C.; van der Hilst, Floor

*Published in:*  
Renewable & Sustainable Energy Reviews

*DOI:*  
[10.1016/j.rser.2019.109352](https://doi.org/10.1016/j.rser.2019.109352)

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*Document Version*  
Publisher's PDF, also known as Version of record

*Publication date:*  
2019

[Link to publication in University of Groningen/UMCG research database](#)

### *Citation for published version (APA):*

Brinkman, M. L. J., Wicke, B., Faaij, A. P. C., & van der Hilst, F. (2019). Projecting socio-economic impacts of bioenergy: Current status and limitations of ex-ante quantification methods. *Renewable & Sustainable Energy Reviews*, 115, [109352]. <https://doi.org/10.1016/j.rser.2019.109352>

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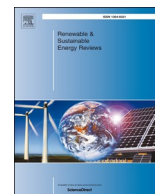
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## Projecting socio-economic impacts of bioenergy: Current status and limitations of *ex-ante* quantification methods



Marnix L.J. Brinkman<sup>a,\*</sup>, Birka Wicke<sup>a</sup>, André P.C. Faaij<sup>b</sup>, Floor van der Hilst<sup>a</sup>

<sup>a</sup> Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 BD Utrecht, the Netherlands

<sup>b</sup> Energy and Sustainability Research Institute, University of Groningen, Blauwborgje 6, 9747 AC Groningen, the Netherlands

### ARTICLE INFO

#### Keywords:

Sustainability  
Certification  
Bioenergy  
Social impacts  
Methods  
Projections

### ABSTRACT

The socio-economic effects of bio-energy are not unequivocally positive, although it is one of the main arguments for supporting its expansion. An *ex-ante* quantification of the impacts is necessary for transparently presenting the benefits and burdens of bioenergy before they occur, and for minimising unwanted outcomes. In this article, the status, limitations, and possibilities for improvements in *ex-ante* quantitative research methods for investigating socio-economic impacts of bioenergy are mapped. For this, a literature review to identify relevant indicators, analyse the latest quantitative *ex-ante* research methods, and to assess their ability and suitability to measure these indicators was performed. The spatial aggregation of existing analyses was specifically considered because quantitative information on different spatial scales shows the geographic distribution of the effects. From the 236 indicators of socio-economic impacts spread over twelve impact categories that were found in this review, it becomes evident that there are clear differences in the *ex-ante* quantification of these indicators. The review shows that some impact categories receive more attention in *ex-ante* quantification studies, such as project-level economic feasibility and national-level macroeconomic impacts, while other relevant indicators have not been *ex-ante* quantified, such as community impacts and public acceptance. Moreover, a key blind spot regarding food security impacts was identified in the aggregation level at which food security impacts are quantified, which does not match the level at which the impacts occur. The review also shows that much more can be done in terms of *ex-ante* quantification of these impacts. Specifically, spatial disaggregation of models and model collaboration can extend the scope of socio-economic analyses. This is demonstrated for food security impacts, which shows the potential for future household-level analysis of food security impacts on all four pillars of food security.

### 1. Introduction

Modern bioenergy is seen as a solution to mitigate climate change, increase energy independence, and stimulate the economy [1–3]. The scientific and political debate on bioenergy has primarily focused on climate change and other environmental impacts of bioenergy (e.g. Refs. [4,5]); however, socio-economic development is an integral aspect of sustainable development and should be considered in this context as well [6–8]. Although countries with a bioenergy mandate expect bioenergy to contribute to a number of socio-economic goals, such as domestic energy security, job creation, and rural development [1,9], the socio-economic impacts of bioenergy are not unequivocally positive [10–13]. Previous studies have identified negative socio-economic impacts, such as competition with food production and disregard for local land rights [9,14–16].

Hence, principles and certification schemes for sustainable bio-energy feedstock production and conversion have been introduced to avoid negative impacts of bioenergy [17–19]. Certification schemes, like the Roundtable on Sustainable Biomaterials (RSB) [20–22], Roundtable on Responsible Soy [23], and Bonsucro [24] have set sustainability standards that need to be met by producers. Although these certification schemes include socio-economic impacts of bioenergy, they focus more on the environmental impacts [17,25–28]. Further, the principles on socio-economic impacts are often formulated as general principles that are vague and cannot always be quantified [11,25–27,29]. For example, multiple certification schemes (e.g. Refs. [24,30]) have set employees' freedom from discrimination as one of their criteria. The availability of a company policy document against discrimination is enough to meet the criteria, without a requirement for measuring whether discrimination actually takes place. However,

\* Corresponding author.

E-mail addresses: [m.l.j.brinkman@uu.nl](mailto:m.l.j.brinkman@uu.nl) (M.L.J. Brinkman), [b.wicke@uu.nl](mailto:b.wicke@uu.nl) (B. Wicke), [a.p.c.faaij@rug.nl](mailto:a.p.c.faaij@rug.nl) (A.P.C. Faaij), [f.vanderhilst@uu.nl](mailto:f.vanderhilst@uu.nl) (F. van der Hilst).

<https://doi.org/10.1016/j.rser.2019.109352>

Received 24 March 2019; Received in revised form 5 August 2019; Accepted 22 August 2019

Available online 18 September 2019

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### Abbreviations

CGE	Computable General Equilibrium
IO	Input output
PE	Partial Equilibrium
SAM	Social Accounting Matrix
(s)LCA	(social) Life Cycle Assessment

quantitative information on the size of the impacts helps understand the scale of an effect and to transparently weigh the positive and negative aspects of bioenergy implementation [11,31,32]. The quantitative information on the socio-economic effects of bioenergy using objective measurements of the socio-economic impacts can then help facilitate and inform the decision-making processes [29,33,34].

Studying the present and past bioenergy projects to determine success factors and barriers can help stimulate the sustainable production of bioenergy. Despite that, to avoid negative impacts or overly optimistic expectations [1,35], the direction and magnitude of the socio-economic impacts of the future development of bioenergy needs to be assessed before actual production. *Ex-ante* knowledge of the potential positive and negative impacts of bioenergy and the balance between the two enables policymakers to minimise undesirable impacts.

Although there is consensus on the key socio-economic areas of concern regarding bioenergy [11,17,18,36], there is less agreement on the indicators that could and should be used to measure the socio-economic performance of bioenergy supply chains [10,17,29,37,38]. The impacts of bioenergy are diverse and cannot be characterised with a single comprehensive value. Therefore, each potential socio-economic impact is described by multiple indicators that account for the various dimensions of each socio-economic impact [11,39–41]. Securing a consensus on the clear indicators of potential socio-economic impacts can help formulate sustainability criteria and measure compliance [38]. This helps promote the overall sustainability of bioenergy [29,38,42].

The socio-economic impacts of bioenergy are not evenly distributed geographically. The impacts at the spatial aggregation level must be considered when including the geographic distribution of the socio-economic impacts in an analysis [11,43–46]. Assessing socio-economic effects at a high aggregation level can obscure regional variation, because the average would smoothen the regional differences, making it impossible to consider the distribution of the effect [47,48]. In contrast focussing only on the effects of a specific bioenergy project in the production region itself would neglect the effects that occur outside that area [49]. Furthermore, a focus on only the region with bioenergy ignores the effects that are indirectly caused by bioenergy (e.g. reduced demand in sectors supplying to the fossil fuel industry) and the cumulative effects of multiple bioenergy projects in a country, such as effects on food prices. The potential effects need to be analysed at various spatial scales to be able to comprehensively capture the socio-economic impacts of bioenergy. Information on the spatial distribution of the socio-economic effects can help avoid a disproportionate accumulation of negative impacts in a specific area.

*Ex-ante* assessment of the socio-economic impacts of bioenergy requires using methods and models that translate scenarios and assumptions of bioenergy implementation to effects on the various indicators. The selection of a method or combination of methods is important for the quantification of the impacts, as all methods have specific strengths and weaknesses, which affect their ability and suitability to quantify the socio-economic indicators. Such methods vary on some aspects, such as the indicators to be quantified, data inputs required, inclusion of indirect effects, and spatial scales to be included. This means the selection of a method also affects the final outcome of the assessment [50]. Currently, there is no overview of the available methods for quantitative *ex-ante* assessment of socio-economic impacts

at different spatial scales and an assessment of their suitability and ability that would help identify the blind spots and associated knowledge gaps.

The shortcomings discussed above hinder agreement on the appropriate indicators of the socio-economic impacts of bioenergy at the relevant scales and the methodology for their quantification. Therefore, this paper aims to map the current status of quantitative *ex-ante* research on the socio-economic impacts of bioenergy, its limitations, and options for improvement. For this, a literature review is performed, to identify relevant indicators, analyse the latest *ex-ante* quantification methods and tools, and assess their ability and suitability to assess these indicators at different spatial scales.

## 2. Material and method

The approach for this literature review consists of two parts. In the first part, relevant indicators of the socio-economic impacts of bioenergy were selected. In the second part, available methods and their ability and suitability to quantify the relevant socio-economic impacts at different spatial levels were identified.

The first step was to make an overview of the socio-economic impacts of bioenergy based on previous reviews of sustainability criteria for bioenergy (e. g. Refs. [1,11,51,52]). This overview made it possible to later cluster the indicators per impact and to identify potential blind spots where no relevant indicators are available for an identified impact. The impacts that were mentioned in at least two different studies were included as the list was meant to be exhaustive, but not too disaggregated.

Those indicators of socio-economic impacts of bioenergy were considered *relevant* for *ex-ante* quantification if they a) reflect the effects<sup>1</sup> of bioenergy b) are included in certification schemes or agreed upon in stakeholder consultation processes, and c) can be assigned a numerical value. Certification schemes and stakeholder consultations represent the indicators that the public, policymakers, companies, and other stakeholders consider most important [53]. To obtain the list of relevant indicators, an overview was made of all indicators of the socio-economic impacts of bioenergy that were identified in the previous step based on the previous studies, as well as the certification schemes and standards for good practices (e.g. Refs. [21,30,54,55]).

Similar indicators were merged into one indicator to avoid duplication. To cull a long-list of indicators to a list of relevant indicators, those indicators that did not meet the following criteria for relevance were removed (as illustrated in Fig. 1):

- 1) the indicators that reflect an attribute of the bioenergy project, rather than an impact, conform Meyer et al. [19].
- 2) the indicators that require a qualitative assessment, and
- 3) the indicators that have not been included in a certification scheme or named by stakeholders in a stakeholder consultation process.

In the second part, the studies were reviewed that quantified *ex-ante* the socio-economic impacts of bioenergy to get an overview of *available* methods and the spatial level at which these are used. Studies quantifying one or more socio-economic impacts of bioenergy were selected using the Scopus search engine in April 2018. Only studies published after 2014 were selected, to include only the most recent literature. The used search terms included the name of each impact and terms related to the list of relevant indicators (for a complete overview, see Table

<sup>1</sup> This is analogous to the categorisation of Meyer et al. [19] who assessed the environmental indicators of bioenergy certification schemes. Since some studies and certification schemes are designed to assess the sustainability of an ongoing project, they contain indicators that reflect properties of management or production (e.g. the availability of a management plan), rather than the impacts of bioenergy.

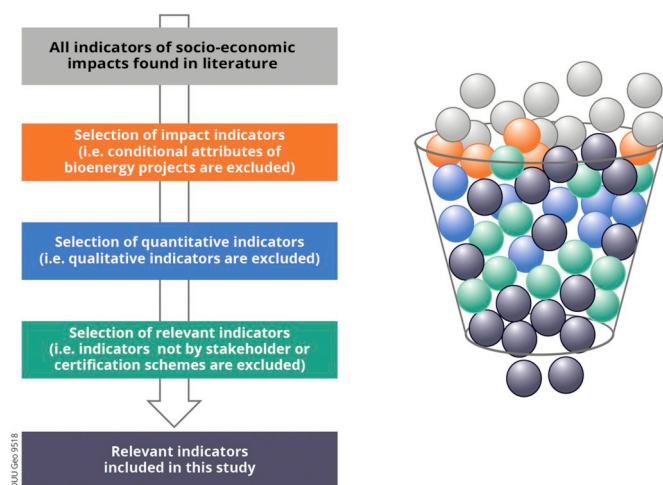


Fig. 1. Selection process of relevant indicators of socio-economic impacts of bioenergy.

A.1). These were combined with the terms ‘bioenergy’, ‘biomass’, ‘biofuel’, ‘biodiesel’, ‘ethanol’, and ‘charcoal’. This yielded around 400–2700 papers per impact category (see Table A.1). Papers whose title and abstract were unrelated to this research were discarded. The selection of sources was then narrowed down by excluding studies that did not focus on *ex-ante* assessment. From the remaining papers, the assessed indicators, the method used, and the spatial scale of the study were recorded, i.e. the level at which the analysis was done, and the results presented (e.g. continental, local, or national level). From the method and discussion sections of these selected papers and review studies, the potential, limitations, strengths, and weaknesses of the methods, i.e. their *suitability* to *ex-ante* quantify the socio-economic impacts of bioenergy, were then discussed. This discussion also included opportunities to improve the *ex-ante* quantification methods.

### 3. Results

#### 3.1. Relevant indicators

13 socio-economic impacts categories for bioenergy were identified: employment and income, food security, macroeconomic development, rural economic development, energy access, energy independence, economic feasibility, health and safety, land rights, working conditions, social acceptability, equal opportunities, and community impacts. For these impacts 236 indicators were mentioned in reviews, certification schemes, and guides of good practice. Table A.2 in the appendix gives an overview of all indicators. Of these 236 indicators, 46 are considered relevant, which means they reflect the effects of bioenergy, are included in certification schemes or agreed upon in stakeholder consultation processes, and a numerical value can be assigned to them. This list was obtained (see Table 1) by removing those indicators that: a) do not reflect impacts (78), or b) are not quantifiable (32), or c) are not included in certification schemes or mentioned by stakeholders (80), as illustrated in Fig. 2. Table 1 gives an overview of the 46 indicators that are considered relevant.

The highest number of relevant indicators was found for employment and income, with nine relevant quantitative indicators that provide insight into the effects on this category. These relevant indicators contain the whole spectrum of impacts: from the number of jobs created and lost in other sectors to information on who benefits from these jobs (e.g. locals or migrants) and the income generated for the employees. The indicators for employment and income are also the indicators mentioned the most in the literature, and are often mentioned as important by the stakeholders (e.g. for food security effects, the indicators reflect the four pillars of food security—availability, access, utilisation

and stability—identified by the United Nations Food and Agriculture Organisation (FAO) which means all aspects of the issue are included [56]. For land rights, working conditions, economic feasibility, community impacts, energy access, and equal opportunities, only two to four relevant indicators were identified, but there is a high consensus on each of these indicators, illustrated by the large number of sources that include them. For health and safety, four relevant indicators were identified, but none of them had been named more than three times. Although macroeconomic impacts, rural economic development, and energy independence are often the rationale used for implementing bioenergy, few relevant indicators are available, and they are seldom mentioned.

Social acceptability is the only impact category for which no relevant indicator was found, since the indicators that have been found (e.g. commitment to ethical conduct [30], effective stakeholder participation [6,10], transparency [6,57]) are either qualitative or not included in a certification scheme or mentioned in a stakeholder consultation process.

#### 3.2. Ability to quantify

In total, 218 studies that contained an *ex-ante* quantification of relevant socio-economic indicators were reviewed. As some studies have quantified multiple indicators, a total of 474 *ex-ante* quantifications was analysed. The indicator that is quantified the most is profitability, which is included in over 50 of the selected studies.

From the actual quantification of the indicators in the various studies (see Table A.3 in the appendix and Fig. 3), it is shown that macroeconomic impacts, employment and income, and rural development are quantified the most often and at almost all spatial levels. For macroeconomic impacts, there are many methods available to quantify the four indicators (see Table 1 and Table A.3); although most studies use input-output modelling in combination with other methods.

No study was found that *ex-ante* quantified the community impacts of bioenergy. Although management has a strong influence on the outcome of this indicator, it is difficult to quantify it, which increases the uncertainty. This also renders the projections of this indicator less valuable.

Other indicators that were not found to be quantified *ex-ante* are:

- ratio of local and migrant workers, and ratio between permanent and temporary jobs (in employment & income);
- seasonality of hunger (in food security);
- capacity of infrastructure (in economic feasibility);
- crime, indoor wood cooking, risk of HIV and other diseases (in health and safety);
- education provided to employees (in working conditions).

For rural development, equal opportunities, and health and safety categories, this means only two indicators are quantified *ex-ante*, and for working conditions, just one. For employment and income, the absence of these two indicators means that two of the three indicators for the social distribution of employment are not quantified, with only the ratio of skilled/unskilled employees being quantified. This indicates that *ex-ante* quantification of employment and income impacts of bioenergy are not comprehensive.

Most indicators are quantified using a regional- or national-level method. There are exceptions to this. For example, profitability and total investment are almost always quantified at the project level, as that is where these impacts occur and the methodology applied—cash flow analysis can quantify the profitability at the project level. Food prices and trade, however, are usually quantified at the national or higher level, although the impacts could be from local to global level [61]. This means lower aggregation level impacts are not included in the current methods, and the geographic distribution of these effects have not been quantified *ex-ante* in the reviewed studies.

**Table 1**  
Overview of the relevant indicators of socio-economic impacts of bioenergy and their units of measurement. The certification schemes, and stakeholder consultations, and previous studies that include these indicators are presented.

Impact category	Indicator	Unit	Stakeholder	Certification	Source
Employment & Income	Household income	€ dy <sup>-1</sup>	[58] <sup>a</sup>	[21]	[6,21,59-61]
	Job loss of other activities	# <sup>b</sup>		[21]	[21,61]
	Ratio between local/migrant workers	%		[62]	[11,51,52,62-64]
	Contribution of feedstock sales to household income	%/€ dy <sup>-1</sup>	[41] <sup>c</sup>		[10,11,41,57]
	Job permanent (in the bioenergy sector or company)	#/# MJ <sup>-1</sup> /fte/# ha <sup>-1</sup>	[41,65,66] <sup>d,e</sup>	[23,62]	[6,11,41,67,68] [1,23,57,59,62,64]
	Ratio permanent/temporary (casual/daily) jobs	%	[41]		[11,41,51,63]
	Ratio skilled/unskilled jobs and availability thereof	%	[41]		[11,41,51,67,68]
	Total wages in the sector	€	[65]		[11,68]
	Wage levels at bioenergy company, compared to minimum or median wage	%/€ dy <sup>-1</sup>	[41,66]	[23,30,55,62]	[11,23,24,29,30,41,51,52,55,62,64,69]
	Change in area of food crops	ha/%		[22]	[11,22]
Food security	Change in calorie/nutrient deficit score	gr cap <sup>-1</sup> day <sup>-1</sup> /kcal cap <sup>-1</sup> day <sup>-1</sup>		[22]	[22,67,70]
	Change in yields of main staple crops	t ha <sup>-1</sup>		[22]	[11,22]
	Lowest monthly calorie deficit/seasonality of hunger	kcal cap <sup>-1</sup> dy <sup>-1</sup>		[22]	[22]
	Price of national food basket	Δ%/Index/€/€ cap <sup>-1</sup> dy <sup>-1</sup>	[37,41]		[10,11,22,41,67,68,70]
	Supply of national food basket	t/%/kcal	[37,41]		[11,41,67,70]
	Change in GDP	€	[65]		[10,11,68]
	Sector contribution to GDP or GRDP	€/%	[37]		[11,64,70]
	Trade volume	€ yr <sup>-1</sup>	[65]		[6,60]
	Gross value added	€ MJ <sup>-1</sup> /%	[41]	[24]	[11,24,41,63]
	Bioenergy to expand access to modern energy services	Δ%	[37,65]		[10,11,59,61,70]
Rural economic development	Share of population that has increased access to energy	l yr <sup>-1</sup> /MJ yr <sup>-1</sup> /%	[41]	[62]	[10,11,41,62]
	Change in fossil fuel imports	Δ %	[41]		[1,11,41]
	Energy diversity/diversification of the energy mix	MJ yr <sup>-1</sup> /€ yr <sup>-1</sup> /t yr <sup>-1</sup>	[37]		[1,61]
	Change in consumption of fossil fuel and traditional biomass	(Herfindahl) index/MJ bioenergy in TPES	[41]		[1,11,41,60]
	Productivity/resource efficiency	MJ yr <sup>-1</sup> /€ yr <sup>-1</sup>	[41]		[41,59]
	Capacity of infrastructure and logistics for distribution of bioenergy	t ha <sup>-1</sup> /MJ ha <sup>-1</sup> /€ MJ <sup>-1</sup>	[41,58]	[24]	[6,11,24,41,52,60]
	Total investment	#/MJ yr <sup>-1</sup>	[41]		[21,41,59,61]
	Profitability (yearly, net present value, return on investment, payback period, internal rate of return)	€ yr <sup>-1</sup> /€/%/year	[58]		[11]
	Crime rate	%	[58,65]		[6,11,70]
	Indoor wood cooking	Δ %		[21]	[10,21]
Health & Safety	Change in mortality and burden of disease attributable to indoor smoke	%	[41,57] <sup>g</sup>	[22]	[22,59,61]
	Risk of HIV/aids and other diseases	%		[21]	[11,41]
	Traffic safety	# accidents		[21]	[10,21]
	Expansion of biofuel feedstock over other crops	ha/%	[41]		[21]
	Loss of natural resources and grazing land	ha		[21]	[11,21,41,64]
	Number of land conflicts	#		[21]	[10,21]
	Share of land acquisitions that comply with formal or socially accepted procedure regarding absolute numbers and area	%	[66]	[30]	[10,11,30,63,64,71]
	Number of work related accidents and health issues	# yr <sup>-1</sup> per 1000 employees/time lost to accidents		[24]	[11,24,51,63,69]
	Incidence of occupational injury, illness and fatalities	#/%/# ha <sup>-1</sup> /# MJ <sup>-1</sup>	[41]		[11,41,64]
	Training and/or education provided to employees	%/# yr <sup>-1</sup>	[41,58,65]	[54]	[10,11,41,51,54,62,63]
Equal opportunities	Change in unpaid time spent by woman and children in collecting biomass	hrs household <sup>-1</sup> week <sup>-1</sup>	[41]	[22]	[11,22,41]
	Female participation (in a type of work, sector, company, management)	%		[23]	[11,23,51]
	Share of women wages compared to men's	%	[65]	[23,62]	[11,23,29,62,64]

(continued on next page)



Table 1 (continued)

Impact category	Indicator	Unit	Stakeholder	Certification	Source
Community Impacts	Access to water supply Community investment	% €		[21,22,30] [62]	[10,21,22,30,52,64,69,70] [11,62]

<sup>a</sup>The indicators that were used in the final indicator list of Vaidya & Mayer [58] were those supported by the stakeholders.

<sup>b</sup>The symbol # signifies a unit that is counted (i.e. number of).

<sup>c</sup>CBEP [41] is a tool designed for stakeholders, therefore all indicators are included.

<sup>d</sup>Gaitán-Cremaschi et al. [65] determined the importance of issues based on a stakeholder consultation. Issues were considered important when at least 4 out of 5 on a Likert scale.

<sup>e</sup>Manik et al. [66] the indicators with the highest weight were selected as relevant.

<sup>f</sup>The indicators considered as “most relevant” or “very relevant” in Van Dam et al. [37].

<sup>g</sup>From the study of Baudry et al. [57] those indicators were included that were named by at least half of the stakeholder groups.

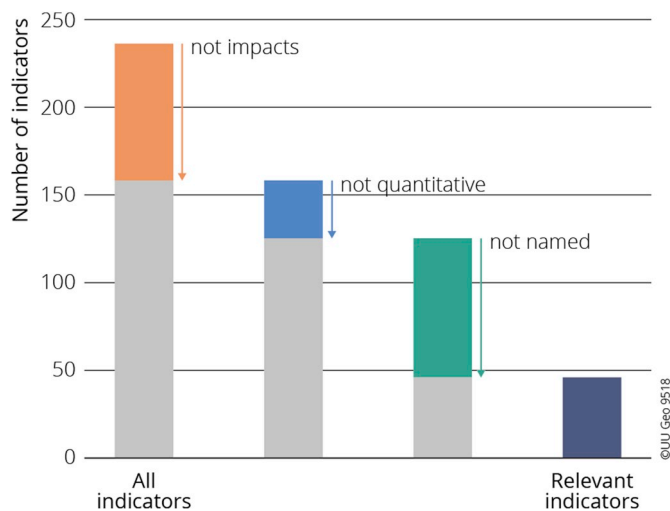


Fig. 2. Process to cull the long-list of 236 total indicators to the list of 46 relevant indicators.

### 3.3. Suitability

This section focusses on the macroeconomic models [input-output (IO), computable general equilibrium (CGE) models and partial equilibrium (PE) models], because studies employing a macroeconomic model either alone or in combination with other methods, cover almost the entire spectrum of socio-economic impacts (see Fig. 3 and Table A.3 in the appendix). The suitability of the methods are evaluated based on its operation and limitations, the indicators it addresses, the spatial levels it can be applied at, and how the suitability of the method for *ex-ante* quantification of socio-economic impacts of bioenergy can be further extended and improved by combining with other methods.

#### 3.3.1. Input output models

An IO model consists of a static overview of all deliveries to and from each economic sector in a single geographic area; it links the additional demand proportionally to extra production in all supplying sectors [72,73]. IO models are used to calculate the socio-economic impacts of bioenergy because they can differentiate between direct, indirect, and induced effects<sup>2</sup> and, are relatively easier to use than CGE and PE models and can include multiple impacts [47,73,74].

On a national level, an IO model is generally used to determine the effect on GDP [47,73–83] or regional value added [47,77,79,83–87]. The IO approach can be extended to other socio-economic impacts by relating the economic activity in a sector to the socio-economic impact (e.g. employment per million dollar) [73]. For example, job creation (e.g. Refs. [47,79,83,86,87]), job loss in other sectors [88], educational level [89], occupational accidents [90], and traffic safety [91]. To apply this method, sectoral data on these impacts are required. Such data can be provided by the social hotspots database [69], which contains sectoral data on socio-economic impacts that can be coupled to the outcomes of an IO model [28,69,89].

An IO model is based on the economic interactions between specified sectors in the social accounting matrix (SAM) for a specific area, meaning socio-economic impacts can be calculated only for that area and spatial level without interaction with the rest of the world. Multi-region IO models broaden the IO approach by including the interaction between the sectors in various countries (e.g. Ref. [74]) or regions

<sup>2</sup> Direct effects are from the expansion of the bioenergy sector, indirect effects are those that occur as a result of additional economic activities in the supplying sectors, including the suppliers of the suppliers, and induced effects are from spending the additional income that households earned from the direct and indirect activities [47,73].



Fig. 3. Relative frequency of use of a spatial aggregation level (left) or quantification method (right). The size of a bubble reflects the number of studies with a specific combination of impacts, methods, and spatial scale.

within a country (e.g. Refs. [47,77]). This helps identify areas where the effects of bioenergy materialise (e.g. where employment will increase) and activities that generate economic activity elsewhere (i.e. cause the largest spill-over effect) [47,74,77,80,83,92]. The downside of the additional information on the distribution of the socio-economic effects over different regions or countries, is the reliance on generally poor-quality trade data and exchange rate effects [93].

One limitation of IO models is the time lag in the availability of data. Owing to the data intensity for producing SAMs and the infrequent updates the data are not current. This means new developments, such as new or rapidly-expanding sectors (e.g. bioenergy) and their interactions with other sectors, are not covered well. Furthermore, due to their static nature, IO models cannot endogenously incorporate technical progress (e.g. more efficient production methods) or structural changes to the economy [87,94]. Changing the technical coefficients of the model can help include technical change and thereby make the IO model more accurate and suitable for projecting socio-economic impacts [95]. Updating the technological coefficients can show the effects of mechanisation in feedstock production on employment [47].

Although in practice, the additional demand for bioenergy leads to effects in other sectors through price dynamics, competition, and substitution, this effect is not included in IO models [96,97]. This can result in overstating the size of the socio-economic impacts of bioenergy [97]. By linking the IO model to other models (e.g. CGE or land use) or using the outcomes of these models, the IO model can take price dynamics, competition, and substitution effects into account. The other models can help determine the size [98,99] or regional distribution [47,84] of future bioenergy demand as input to the IO model [100]. This improves the quality and the spatial detail of the calculated socio-economic impacts, when combined with a multi-regional IO model.

### 3.3.2. Computable general equilibrium models

CGE models are a type of macroeconomic models that include a global coverage<sup>3</sup> of all sectors of the economy and the economic

interactions of supply, demand, and competition between the sectors that lead to a state of equilibrium [101]. CGE models are used for studying the socio-economic impacts of bioenergy because of their ability to include indirect effects, and the global scope matches the chain of effect of bioenergy [102–107]. CGE models are most suitable for mid-term analysis, typically 10–20 years in the future.

For socio-economic impacts of bioenergy, CGE models are usually used to calculate change in GDP [105–116], price and supply of food [101,105–107,109,114,115,117,118], trade volume [101,106,107,112], and wages [105,107,109,112,114] because of bioenergy expansion (see Fig. 3 and Table A.3). The effects that are calculated directly by the model are changes in price and production volume of economic sectors and the interactions between the sectors. CGE models are limited to monetary interactions that do not correspond well with physical volumes [104]. This means, for example, food is only included based on its monetary value, although the nutritional intensity (nutrients per \$) can vary significantly. This leads to uncertain results as it is difficult to assess indicators based solely on the monetary value of a sector, especially in aggregated sectors. One key example is land use, for which the competition between bioenergy and other sectors is very important. To include other effects (such as job creation) it is possible to use the same method as in an IO model—relating the impact to the economic intensity of a sector [109,119,120].

Most CGE models use national-or-higher-level aggregate data for the interaction between the various sectors. Hence, the effects do not account for variations at lower spatial levels. The same holds true the sectoral aggregation; variation within sectors cannot be detected with a CGE model, even though there will be winners and losers within a sector. It becomes necessary to modify the CGE model to provide more detailed results, including the social or geographical distribution of effects. While most CGE models contain only one household per region, it is possible to derive household-level results by splitting that single household into multiple households in a specific area [107,121]. By differentiating the households according to region, income [122,123], or location (urban/rural [122]), additional information on the social and geographical distribution of the effects of bioenergy can be derived. Another option is to extend the analysis with microsimulations, which

<sup>3</sup> Disaggregated in multiple countries or continents.

does not rely on the disaggregation of top-down SAM to various households, but uses bottom-up data from a household survey to simulate the effects of price and income changes on thousands of different households [107,108,111,124]. This approach can show the distribution of the socio-economic effects for multiple households [125]. Using microsimulations, impacts can be determined at household or local level and can include, for example, household income and poverty rate [105,107,108,111].

CGE models are dynamic, meaning the relations between the sectors can change over time in response to changes in the economy, based on the models' elasticities [113]. Therefore, projections can include the effects of developing technology. However, as these effects are based on historical data, the modifications to the model's elasticities are also confined to those based on historical data. The time lag between the base year and publication year for SAMs is even longer in CGE modelling than in IO, as its production is a more data-intensive process. Bottom-up technology assessment [126] or adaptations from the structure of the sector in other areas [123] can be used to include bioenergy expansion to new areas in a CGE model. Nevertheless, this does not account for all structural changes to the economy in general and agriculture in particular. More sustainable production methods and potential for faster progress in the agricultural sector are not included in the CGE models, although these are important for sustainable bioenergy production, for example, by limiting competition for land (e.g. Refs. [127,128]). Incorporating the potential to reduce negative impacts, either via technology or policy interventions, in the CGE models would enable higher quality assessment of the sustainability impacts. For example, for the effects on food security, competition for land plays a major role.

One basic assumption of CGE models is that an economy tends towards equilibrium. However, this does not exist in practice [119]. Further, disregarding the adjustment path towards equilibrium might mean overlooking periods of extreme food price volatility, food shortages or other potential negative effects of bioenergy in the short run [129]. The equilibrium assumption has implications specifically for the projections on employment because labour is not a normal commodity [116,119] as employees cannot be as easily transferred from one sector or region to another as capital can. Thus, additional employment in a specific sector does not necessarily compensate for job losses in another sector or region [119]. This means unemployment from displacement of production (e.g. in the fossil fuel sector) is likely to be underestimated in a CGE model, especially in the short term, because labour markets require time to adjust. These limitations have a smaller impact, -the longer time-frame used in the CGE model [104]. One option to address this issue is to distinguish different skill levels in employment and thereby, make labour a less homogeneous good in the model [108].

Linking a CGE model to other models can help overcome the lack of detail in the relations between the sectors in the global model. For example, by linking a CGE to an energy sector model, such as MARKAL [116], a biophysical model [105,130], a land use model [47,131] or detailed technical modelling of biofuel production chains [130], the modelling outcomes of the CGE can be more spatially explicit or better account for variation within economic sectors, which is not included in the economic model itself.

### 3.3.3. Partial equilibrium

PE models are similar to CGE models -they also use the laws of supply and demand to establish a new equilibrium after an economic shock has been introduced. Regardless, instead of the highly aggregated sectoral that is used in a CGE model, only a limited number of sectors is included in a PE model, and these are represented in greater detail. Modelling of the sector(s) included in the PE model is more extensive, and includes many products and interrelations between sectors; hence, PE models are typically used for longer-term analyses (up to 40 years).

PE models are most commonly used to calculate the impacts on

trade [132–140], food prices, and food supply [98,134,135,140–146]. Most studies present the results on national [98,116, 132–139,144,145,147–150] or higher [99,140–143,146] spatial aggregation levels. The increased detail in the energy sector, compared with CGE or IO models, helps provide projections on, for example, the role of bioenergy in the energy mix [137,151,152], change in fossil fuel imports [99,135,149,151] and changes in the use of traditional bioenergy [145,152]. Further, a PE model can be adapted to include spatially explicit land-use modelling, to reflect the competition between various land uses (e.g. Ref. [153]). As competition takes into account local suitability, the projections of land use are more detailed than in a CGE model. PE models are, for example, used to project reduction in land for food production [143,150], or to determine where current agricultural land is replaced by bioenergy feedstock [148,149,154].

PE models include only a partial representation of the economy and assume fixed prices and income in other sectors (i.e. *ceteris paribus*). This means socio-economic effects for the other sectors are not included. However, in reality, the effects of bioenergy are not limited to the few sectors that are included in the PE model. This problem can be partly mitigated by combining the global modelling of a CGE model with the detailed analysis of a PE model [116], or combining several PE models [140].

### 3.3.4. Bottom-up and process modelling

Bottom-up models are a heterogeneous group of various analytical and process models. One commonality of the methods is that they start with a detailed representation of the interactions between inputs and outputs and do not contain explicit modelling of interactions outside the production chain, such as market-based effects [104,155,156].

The social-economic impacts are analysed starting from the technical performance of the bioenergy supply chain and its energy and mass balance. The technical model can then be used to project the total investment (e.g. Refs. [157–160]) and profitability (e.g. Refs. [161–163]) of a project. Some studies use special process modelling software, such as ASPEN (e.g. Refs. [161,164]), or a spreadsheet model [161,165,166] for modelling and cost estimation using the share of labour in the total cost, or extrapolating the labour requirement to estimate job creation at the project level (e.g. Refs. [167–169]), the ratio between skilled and unskilled employees [168], or wages [170,171].

These bottom-up models are almost exclusively used for project-level estimations for the near future. Although the methods are rigorous and includes all aspects of the production process, they cannot account for indirect effects of investment on the rest of a region or country, neglecting the effects of competition and additional production in the rest of the economy [50,172].

Bottom-up modelling can be combined with macroeconomic modelling, such as IO or CGE analysis to account for indirect effects [172,173]. In the latter case, the dynamic changes to the economy can also be included. In such combined approaches, the detail of the process modelling can be integrated with the potential of the macroeconomic models to calculate indirect effects.

### 3.3.5. Cash flow analysis

Cash flow analysis makes an overview of all expected monetary incomes and expenditures and calculates profitability, taking opportunity costs and interest rates of capital into account. It is typically combined with bottom-up and process modelling (e.g. Refs. [174–178]), it is relatively easy, and transparent. The data requirement can be low, depending on the depth of the process modelling, although for new processes, the availability can be low and the data uncertain. Cash-flow analysis is usually done at the project level. Combining cash flow analysis with Monte Carlo simulation can provide information on the uncertainties of outcomes [179].

### 3.3.6. Social life cycle assessment

Another distinctive set of methods are life cycle assessment (LCA)



and social LCA (sLCA) [180,181]. LCA is a standardised method that inventories all physical and energy input and output flows of specific production process and calculates their environmental impacts. In the context of socio-economic impacts of bioenergy, only the impacts of fossil fuel use and its reduction [182–184] and human health effects for employees [65] or the general public are relevant. For example, respiratory diseases caused by sulphur dioxide and NO<sub>x</sub> emissions from using biofuels in the transport sector [80,183,185,186]. These health effects (expressed as disability-adjusted life years) could be converted to economic damages (in monetary terms), and included in economic modelling (e.g. Ref. [187]).

sLCA is an extension of the LCA framework that relates the input and output of a production process to social impacts instead of environmental impacts [180,188]. Not all studies quantify the impacts, but rather use a narrative to indicate the risk of negative impacts [69,180,188,189]. In bioenergy, job creation [89,90,190], wages [89,90,190], and occupational accidents [89,90,190] have been *ex-ante* quantified using sLCA. These impacts are connected to the production chain, but since no region-specific data are available, the results are presented without specifying the location [51]. (s)LCA focuses on a specific production system, with clearly defined boundaries. This means the cumulative effects or indirect effects on other systems, for example, arising from competition for land, are not included.

Some studies use a hybrid input-output-(s)LCA approach [73,77,89–91,191,192], where the detailed modelling of the production system is replaced with the more general approach of IO modelling [181,193]. This sacrifices detail in the exact inputs and location of production and spatial detail. However, it makes it possible to include indirect effects in a (s)LCA [193]. Further, the process information gathered for the LCA can also be used as an input for the technical coefficients in the IO model.

### 3.3.7. Other methods

A few additional methods have been used to *ex-ante* quantify socio-economic impacts of bioenergy. For impacts at a low spatial level, system dynamics models [75,194–196] and agent based modelling [197,198] have been used. These models represent a bioenergy systems based on the actors and their interactions [199]. Despite that, these are typically applied to explain the present state of a system, *ex-post*, rather than project future responses. Spatially-explicit methods (e.g. Refs. [47,200–202]) have typically been used in combination with macro-economic models. The macroeconomic effects calculated using CGE or IO were converted to spatial effects using land-use allocation methods (e.g. Ref. [47]). Integrated assessment models [203–206] and biophysical [207] models have been used to determine impacts at a global level, to calculate mostly land-use change effects especially relevant for food security. Game theory is relatively new and only one study was found that used this approach in the context of socio-economic impacts of bioenergy - to determine trade impacts [208]. Game theory is generally used to analyse competition and cooperation and, in this sense, could be relevant to analyse the interactions between bioenergy and other agricultural sectors [209,210]. Many studies have used different types of optimisation models [206,211–223], mostly as an extension to bottom-up/process modelling to determine the best achievable outcome. These models can be used to explore the socio-economic effects in an optimal situation [221].

## 4. Discussion

Socio-economic impacts are an integral aspect of sustainability of bioenergy and should preferably be quantified *ex-ante* to enable informed decision making and to stimulate the development of sustainable bioenergy. This study reviewed the state-of-the-art *ex-ante* assessments of socio-economic impacts of bioenergy. Using previous studies, guidelines of good practice, and certification schemes, the relevant indicators and the ability and suitability of methods to quantify these

indicators at various spatial levels, were identified and analysed. The review shows the multiple methods (see Fig. 3) available for *ex-ante* quantification of the impacts of bioenergy (see Table 1). These methods can be applied at different aggregation levels (see Fig. 3), which makes it possible to analyse the geographic distribution of the impacts. The review also identifies the gaps and limitations at specific spatial levels in their ability to quantify *ex-ante* the relevant indicators of socio-economic impacts of bioenergy.

There are some limitations to these findings. When making the overview the applied indicators of socio-economic impacts, not all existing certification schemes and guides for good practice were analysed on the presence of socio-economic indicators. For example the European Commission has already recognised 15 certification schemes to be used for biofuels under the Renewable Energy Directive [224]. Some of these are for specific production chains (e.g. U.S. Soybean Sustainability Assurance Protocol or Roundtable on Sustainable Palm Oil), and can therefore be tailored to these production chains and contain socio-economic impacts that are not relevant in other production chains. However, as some of the most relevant certification schemes are analysed in this study it is unlikely major impact categories were overlooked. In addition, some of these certification schemes recognise biomass that is certified using other schemes as compliant in their scheme (e.g. Ref. [225]). This means there cannot be a large discrepancy between them. Another potential limitation to this study's findings, is that potentially useful methods for projecting socio-economic impacts of bioenergy can have been overlooked. The study focussed on the methods that have been applied in the context of bioenergy. This means, that methods from other fields of research may have been ignored.

The gaps in literature identified in this study are discussed in greater detail in section 4.1. These gaps should be the focus of future studies that aim to quantify the socio-economic impacts of bio-energy. Section 4.2 gives final remarks on *ex-ante* quantification of socio-economic impacts of bioenergy.

### 4.1. Gaps and limitations

***Ex-ante* quantification of social acceptability and community impacts has not been found, but other socio-economic impacts of bioenergy are quantified *ex-ante*.** The absence of quantitative projections is likely a result of the importance of the local context and the specific management choices for the actual performance of (local) projects [3,11]. As these factors may play a large role, the uncertainty of a projection would be greater. Although social acceptability and community impacts are not *ex-ante* quantifiable, it does not mean these should not play a role in decision making. However, neither of these impacts has attracted much support during stakeholder consultations, even when the subject has been explicitly addressed [65,66,226]. Only in the case described by Dale et al. [227], there is some support amongst stakeholders to include public opinion in the sustainability criteria of bioenergy.

**One important aspect in the quantification of socio-economic impacts is the inability to include the social context in *ex-ante* quantitative models.** The social context contains aspects, such as cultural norms, strength of government, and local institutions [27,228–231]. Together with other aspects that can be included in the models, such as the biophysical, economic situation, technological and feedstock choice, the social context also influences the magnitude and importance of the socio-economic impacts of bioenergy [11,232,233]. The social context influences the sustainability criteria used for bioenergy production and their enforcement [27,232]. Many certification schemes demand compliance with local laws, for example, for land acquisition or labour rights. However, for countries with weak legal frameworks or that set a low bar for the sustainability of bioenergy, this demand for compliance with local laws may not guarantee positive effects for the population [27,230,234]. Integrating this social context

in *ex-ante* modelling is a challenge. For models that are calibrated to historical data, such as CGE, PE, and land-use models, the effects of the social context are implicitly included. During the model calibration phase, the model is benchmarked and adapted to reflect past outcomes [153,235]. The real-life data (as opposed to model outcomes), which are used to calibrate the models, indirectly reflect the choices that people made within their respective social context. As a consequence of adapting the models to fit these actual outcomes, the elasticities, which represent the market responses to changes, reflect these choices. Nevertheless, the effectiveness of a calibration procedure depends on the availability of high quality datasets for the model calibration [97,236]. Therefore, future work in the form of monitoring of, say, agricultural, performance is needed to improve data availability and model outcomes. These data can also help better include technological progress in the models.

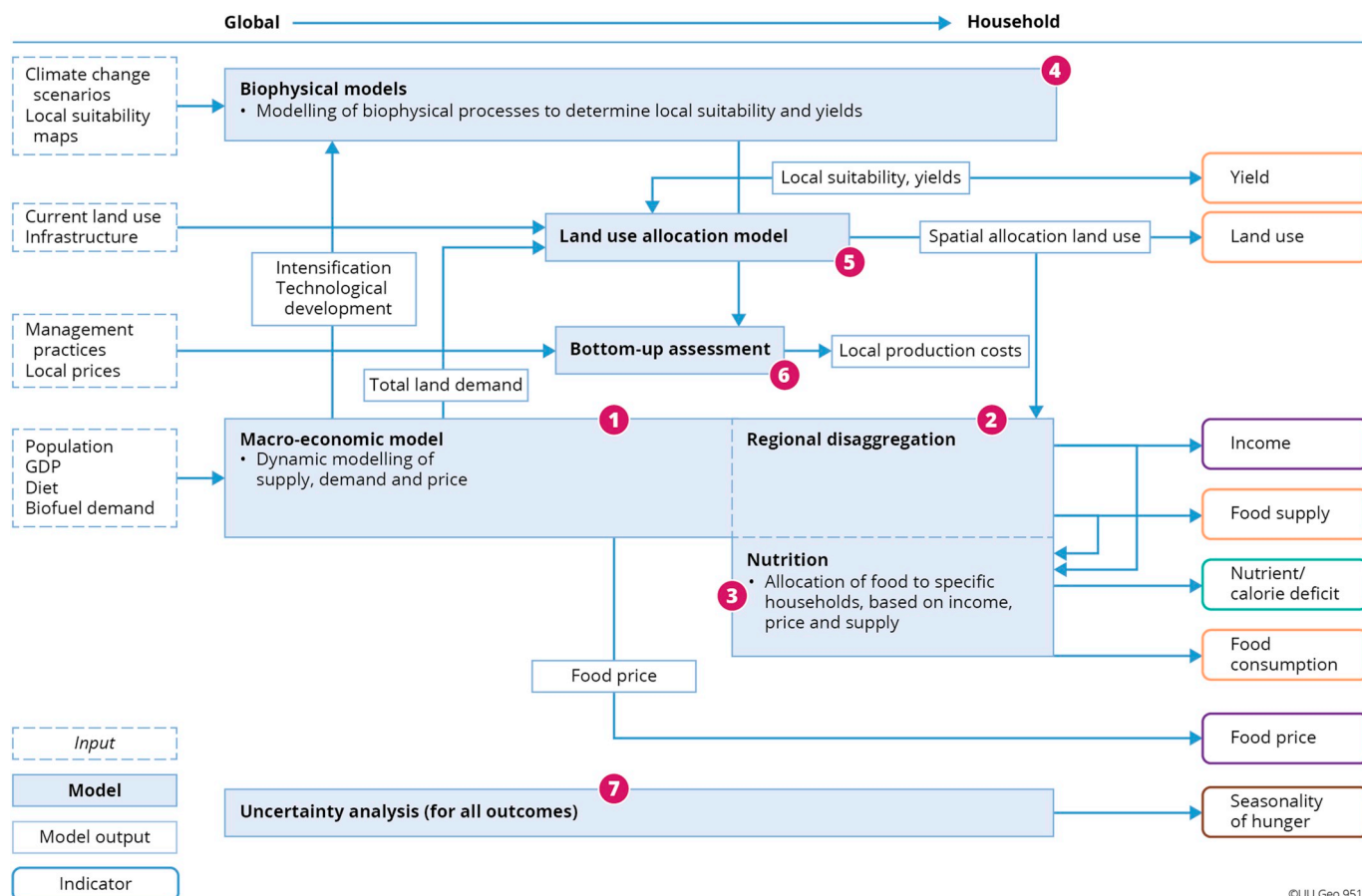
In the context of the environmental performance of bioenergy, Davis et al. [237] used the term ‘management swing potential’ to indicate how much impact management can have on the environmental effects of bioenergy. It can be hypothesised that the management swing potential for socio-economic impacts differs among various impacts, depending on the importance of the management compared to biophysical and social context factors for the specific socio-economic impacts [11,59]. For the socio-economic impacts where the management

swing potential is relatively large (e.g. labour rights or freedom from discrimination), making projections becomes more difficult. This can be partly overcome by varying potential management strategies using scenario analysis to reflect the range in outcomes. This could also be applied to make projections on community impacts, for which no other quantification methods were found.

**Indirect effects are often not properly captured by the models.**

It is important to determine indirect effects of bioenergy deployment, such as on food security, because these are an important part of the total effects. However, only a few methods are able to include these indirect effects. As these effects are often the result of competition or substitution between the economic sectors in the model, macro-economic models can include effects outside the bioenergy sector. Nevertheless, as the spatial detail of these macroeconomic models is relatively low, the indirect impacts are determined at a higher aggregation level. This means that the impacts are not specifically calculated at the lower spatial level where these impacts occur. Inclusion of multiple households in these models or lower-aggregation-level analysis is required to increase the level of detail (see also Fig. 4 or e.g. Ref. [238]).

Additionally, not all socio-economic impacts that can be quantified by the methods are actually presented as results in the studies. For example, IO studies that present the net employment effects of



**Fig. 4.** Model collaboration to overcome the identified blind spots of food security impacts at low aggregation level. A macroeconomic model (e.g. CGE) gives the global context, dynamics, and (indirect) interactions (1). This information can be disaggregated to a lower level (2) for example by distinguishing multiple households within the country, and used to determine the effects on food consumption and nutrition (3), based on the changes in income, prices, and production. The local context is included through a link with a land use model (4) that provides spatial explicit allocation of the land use. A bottom-up model can be used to determine local agricultural and bioenergy processing costs, which can be converted to cost structures to be used in the macroeconomic model, for example, by including local input prices and management practices. Land use allocation is dependent on the local conditions such as the current biophysical conditions (4). To account for the seasonal variation, uncertainty analysis (7) can be applied to provide information on the variations in food supply throughout the year. The colour of the indicators on the right hand-side of the figure relate to the pillars of food security: availability (orange), access (purple), utilisation (green), and stability (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

bioenergy can also calculate the job loss in other sectors [47,88]. However, this is often not included, omitting an important indirect effect. Another example of indirect effects that are not presented by the studies are the health and safety aspects of indoor smoke resulting from use of traditional bioenergy. Increasing household income leads to a switch to other fuel sources [239,240] and, thereby, to better indoor air quality and lower health impacts [241,242]. Other aspects that are linked to income are the time spent by women gathering fuelwood [243,244]. These aspects are not directly included in studies on bioenergy use. Despite that, this would become possible by explicitly linking these impacts to the income effects of bioenergy.

**One key blind spot is the lack of methods to assess the local effects of bioenergy on food supply and price.** Smith and Bustamante [61] have shown that the food security impacts of bioenergy range from local to global. However, to our knowledge, no local- or household-level assessment of the effect of bioenergy on the availability or price of food has been published so far. The only sub-national food security impacts that were found to be structurally quantified *ex-ante* are the effects on agricultural land use [194,201,245,246]. Although this is a useful proxy to show the impact of bioenergy on food availability, it does not include the effects of additional income or a potential switch to a higher yielding crop. As no low-aggregation-level *ex-ante* quantification has been found, it is hard to assess the distribution of food security effects of bioenergy at the aggregation level at which it is most relevant (i.e. households).

**Current methods for *ex-ante* assessment of socio-economic impacts of bioenergy can provide more information than what is obtained, but more work is needed to include the effects on all relevant spatial levels.** It appears that not all socio-economic effects of bioenergy are so far quantified *ex-ante* at the spatial levels where those impacts occur. Regardless, the analysis can be extended beyond what has already been done. Here, it is demonstrated how a combination of different methods can be used to extend the analysis of the socio-economic impacts of bioenergy beyond the current state-of-the-art. This also addresses the blind spots in the assessment of the geographic distribution and illustrates how the distribution of food security impacts of bioenergy can be determined for a specific case.

Six relevant indicators of food security were identified in section 3.1: i) area of food crops, ii) food prices, iii) food supply, iv) calorie/nutrient deficit score, v) yields of main staple crops, and vi) lowest monthly calorie deficit/seasonality of hunger (see Table 1). To quantify these impacts *ex-ante* on a low spatial-aggregation level, potential connections between existing models and are discussed and illustrated in Fig. 4. Fig. 5 shows the spatial level at which each pillar of food security can be quantified.

The scenarios for socio-economic development at the macro level

(population, global economic growth, etc. [203]) and the bioenergy demand for which the food security effects are to be assessed are the starting point for the analysis of food security impacts of bioenergy at the household-level. A macroeconomic model (1, in Fig. 4), such as a CGE or PE model (e.g. Ref. [247]) can account for the dynamics in demand and supply of all sectors in response to the bioenergy demand in such scenarios. This includes the indirect effects in the rest of the economy as a result of this increased bioenergy demand. The economic dynamics of the macroeconomic model lead to national-or-higher-level projections on developments in food demand, supply, and prices as well as the aggregate information on average household income. A disaggregated macroeconomic model (2, in Fig. 4) that spatially disaggregates -regions or income groups (e.g. Ref. [121]) to gain insight in the geographical or social distribution of these effects. The use of a macroeconomic model with sub-national sectors enables the inclusion of selected household types in the economic dynamics of the model (see e.g. Ref. [248]). Disaggregation to household types for specific regions or income groups can provide information on the distribution of the food security effects within a country.

The land use of each crop determined in the macroeconomic model can be spatially disaggregated using a land-use allocation model (5, in Fig. 4) that can operate at the desired spatial level (e.g. Refs. [249,250]). The inputs for the land allocation model are maps of current land use and infrastructure, information on local suitability and yields, for example, from the biophysical model (4, in Fig. 4), and the total land demand in future scenarios. The biophysical models use information on climate, local soil conditions, technological development, and intensification to determine the suitability and potential yields in each location (see e.g. Ref. [251]). The outcomes of the land allocation model can be used to determine land use in the regions of the disaggregated macroeconomic model. Integrating the macroeconomic and land allocation models enable the inclusion of feedback mechanisms between the demand and supply of land. Further, this can help better project yield development and competition for land between among agricultural demands by including both biophysical and economic dynamics that determine yield development. Specific local conditions can be factored into the cost structures for agriculture or bioenergy conversion in the macroeconomic model using bottom-up technology projections (6, in Fig. 4) that are dependent on local prices, management practices and yields (e.g. Ref. [126]).

A nutrition module (3, in Fig. 4) added to a CGE model, for example, through post analysis [120] or microsimulations [252], can project the consumption changes resulting from changes in income, prices, and production. Combining these model outputs with information on the energy and nutrient content of food products can then give the household calorie and nutrient consumption. Comparing this to the

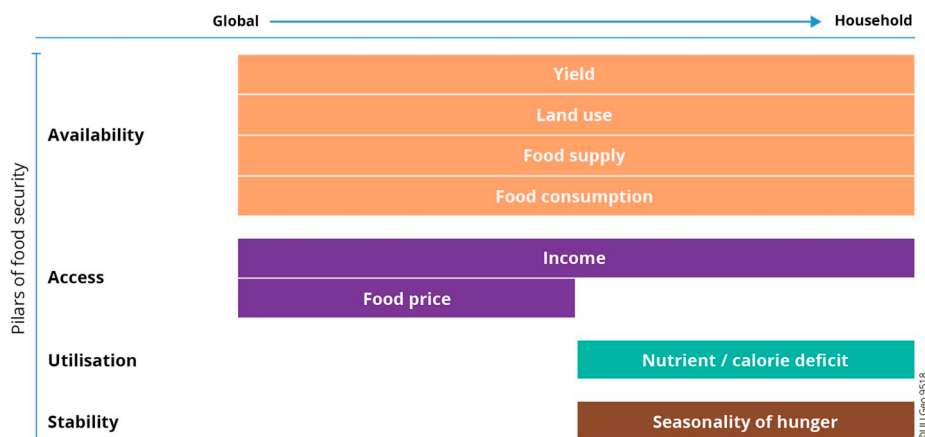


Fig. 5. Aggregation level for *ex-ante* quantification of food security indicators. The indicators are classified based on the four pillars of food security (availability, access, utilisation and stability) as defined by the FAO [56].

recommended nutrient and energy intake then indicates whether there is a surplus or deficit in food consumption. The seasonal variation in calorie intake can be determined in an uncertainty analysis (7, in Fig. 4), where the information on total food supply, with household survey data and for example Monte Carlo simulations are used to determine the likelihood of the food supply dropping below the required level. Fig. 5 presents the levels at which the pillars of food security can be quantified *ex-ante*.

#### 4.2. Conclusions

*Ex-ante* quantification of the socio-economic impacts of bioenergy is an important aspect in the assessment of its sustainability because quantitative information can help present the effects in a transparent and objective manner, providing insight into the trade-offs between the positive and negative impacts. Based on the lessons learnt from this review three recommendations for improved assessment of socio-economic impacts are made: i) extending the analysis to more indicators and aggregation levels; ii) improving the macroeconomic models and their data requirements; and iii) reassessing the role of socio-economic impacts in certification schemes.

To enable a comprehensive *ex-ante* assessment of the socio-economic impacts of bioenergy, more efforts need to be made to improve the quantification of those indicators for which no quantification methods have been found. This could require developing new methods, or as illustrated for food security in Fig. 4, collaboration of existing methods to provide more insights into the distribution on lower aggregation levels. Another option is to explore new indicators that can be quantified *ex-ante* and can be used as a proxy for the missing indicator [253]. For example, use the change in the share of households above a certain income threshold as a proxy for the reduction in health effects of indoor smoke (e.g. Refs. [239–242]).

Extending the analysis to a lower spatial aggregation level and/or other sectors helps show the distribution of the socio-economic impacts, but it is not yet feasible for most cases because data unavailability. Since a CGE, PE or IO model, or a combination of these is the most likely option to *ex-ante* assess the socio-economic impacts of bioenergy at a lower spatial aggregation level, timely availability of social accounting matrices is required. Disaggregated models are only available for specific situations. The data intensity makes it unfeasible to disaggregate a macroeconomic model for each specific study. For low spatial aggregation levels, high-quality data are difficult to obtain and depend on the quality of data collection. In countries with a large informal economy and few resources for gathering data, data collection is more difficult and data quality is often poor. At the same time, these countries are also the most likely to experience negative impacts of bioenergy, which is why it is even more important to have high-quality data and *ex-ante* assessment of socio-economic impacts. This need for better-quality data also applies to technological development in agriculture and conversion processes. Although technological progress can significantly influence the occurrence and level of socio-economic impacts of bioenergy, it is only included with a delay. This makes it more difficult to include the effects of more sustainable practices in *ex-ante* analyses.

Further, the availability of spatial land use information is crucial. Land use dynamics are important to determine the competition for land and other resources. Land use allocation could increase the spatial detail of the socio-economic impacts (e.g. Ref. [47]), but it depends on the availability and the quality of spatial data for current land use and local suitability to properly model the land-use dynamics [131]. This underlines the importance of developing land use and land quality maps of areas where bioenergy can have a direct or indirect impact.

The review of the socio-economic indicators in certification schemes shows that these play a relatively minor role as compared to environmental indicators. Moreover, the socio-economic criteria used are mostly based on past performance, rather than *ex-ante* projections.

However, an *ex-ante* assessment of the socio-economic impacts of bioenergy can help promote the positive impacts and avoid production where negative impacts could occur. Such *ex-ante* assessments can go together with certification as it is equally important to verify the actual production practices. This can help stimulate sustainable production of bioenergy.

#### Acknowledgements

This work was carried out within the Be-Basic R&D Program, which was granted a FES subsidy from the Dutch Ministry of Economic Affairs, Agriculture and Innovation (ELI). The authors want to thank Margot Stoete for her work on the illustrations.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.rser.2019.109352>.

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