Sustainable Agriculture Reviews 30

Olivier Réchauchère · Antonio Bispo
Benoît Gabrielle · David Makowski
*Editors*

# Sustainable Agriculture Reviews 30

## Environmental Impact of Land Use Change in Agricultural Systems

Springer

# Sustainable Agriculture Reviews

## Volume 30

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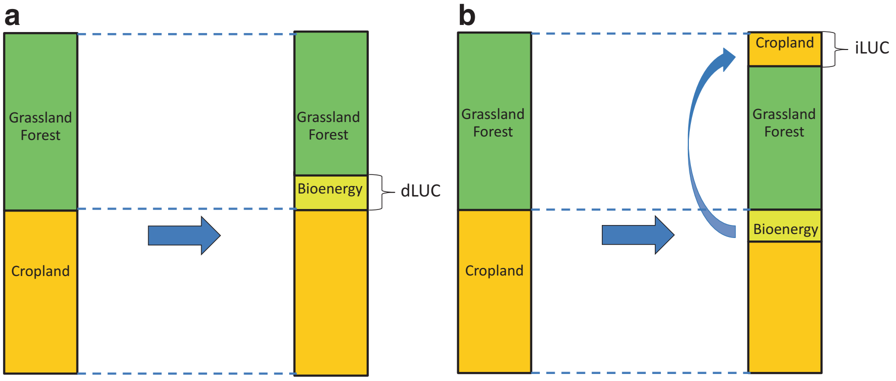
# General Introduction for the Special Volume of SAR

## Overall Research Question

A variety of studies undertaken by both international and French research groups (in France, notably those conducted by ADEME in collaboration with INRA, e.g., De Cara et al. 2012) have demonstrated the importance of considering land-use change (LUC) within environmental impact assessments (van Vliet et al. 2016; Hellweg and Milà i Canals 2015; Liu et al. 2015). Indeed, accounting for the environmental impacts of LUC subsequent to the reorganization of an agricultural system can significantly alter the overall environmental impact assessment for that reorganization. This is the case, for example, in greenhouse gas accounting for the bioenergy sector (Searchinger et al. 2008; Lapola et al. 2010).

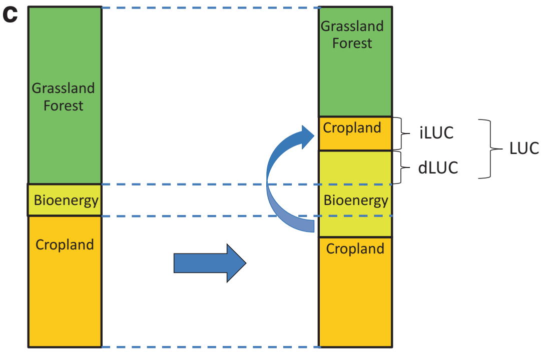
Publications addressing the issue of land-use change (both direct and indirect) are now abundant, particularly with respect to agricultural production. Changes in agricultural practices, whether these involve alterations in existing techniques, a shift from one technique to another, or a more significant reorganization of an overall cropping or livestock system, can result in land-use changes at multiple scales, with attendant environmental impacts. Numerous studies focused on first-generation biofuels have emphasized their environmental impact compared to fossil fuel production and use, primarily with respect to greenhouse gas emissions. More recent studies have examined the environmental impacts of second-generation biofuels (Davis et al. 2012), of increased livestock production (Nguyen et al. 2013), and of urbanization (Toth 2012). These more recent studies seek to calculate the environmental impacts associated with different types of land-use change, generally using similar methodologies as those used in the environmental impact assessments for first-generation biofuels (i.e., biophysical and economic modeling, life-cycle analysis (LCA)).

Two types of land-use change are generally distinguished: direct LUC and indirect LUC (Fig. 1). Direct LUC (dLUC) refers to situations where the expansion of a crop modifies the land-use category, which may previously have been forest or permanent grassland. This thus involves a direct change in land-use category (as



Simplified illustration of a direct LUC situation

Simplified illustration of an indirect LUC situation



Simplified illustration of a system reorganization involving both dLUC and iLUC (based on De Cara, 2012)

**Fig. 1** Schematic representation of how agricultural reorganization can lead to direct LUC (**a**), indirect LUC (**b**), or a combination of direct and indirect LUC (**c**)

defined by the IPCC (2006). Indirect land-use change (iLUC) refers to the effects of changes in agricultural practices or in the end use of agricultural products in an area already devoted to agriculture (e.g., a shift from a food crop to an energy crop) prompting an indirect land-use change in another geographic area (e.g., the replacement of a grassland or a forest by a food crop to compensate for a loss in food production elsewhere).

Indirect LUC can involve reductions or expansions of cultivated land area. Thus, for example, an increase in yields at the local level could allow for the same volume of production from a smaller land area, potentially freeing up land for other uses (Brunelle et al. 2014). Conversely, a decision to redirect a portion of food crop output toward nonfood uses can lead to a shifting of food production to other land areas, potentially resulting in a LUC in a previously uncultivated zone (Lapola et al. 2010; Plevin et al. 2010).

The overall environmental impact of the reorganization of an agricultural system can thus be understood as the sum of (a) impacts resulting directly from implemen-

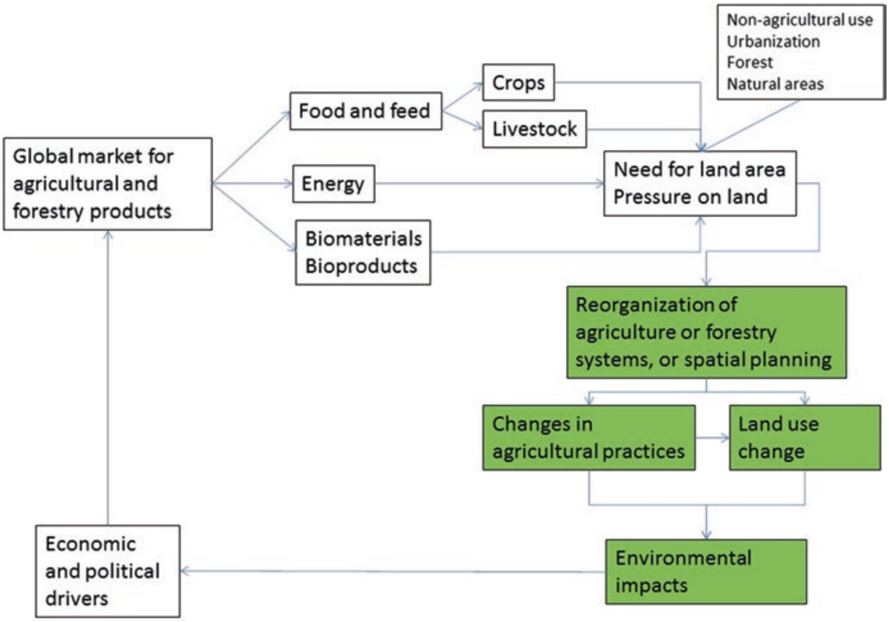


**Fig. 2** Conceptual diagram of factors influencing land-use change

tation of that reorganization plus (b) impacts linked to land-use changes, both direct and indirect, triggered by that reorganization.

Incorporating LUC impacts into environmental assessments is a complex undertaking. LUC is determined by multiple factors including prices, yields, the nature of the agro/ecosystems involved, dietary habits, policy measures and incentives, etc. (Fig. 1). Moreover, although dLUC may be monitored and quantified (e.g., transformation of a natural area into a cultivated system), iLUC cannot, since by definition these are assessed by way of a calculation or a modeling exercise, not through direct observation. Estimating the magnitude of iLUC thus involves making hypotheses as to the consequences of an agricultural reorganization (e.g., via a consequential LCA or a descriptive causal methodology) or simulating different scenarios using models integrating highly diverse types of information (political, economic, biophysical, etc.) (Ben Aoun et al. 2013).

Figure 2 diagrams the principal drivers and interactions giving rise to land-use change. Within the agricultural realm, changes in demand for different food products (including both animal and plant products), changes in energy use, and changes in the use of other biologically sourced materials determine the total productive land area required. Changes in nonagricultural forms of land use can also impact the pressure on cultivated land (e.g., need for housing, other infrastructure). The combined effect of changes in demand for agricultural products, forestry products, and other uses will determine the reorganization of agricultural systems, including land-use changes, the magnitude of which will likewise depend on changes in agricultural practices, notably since these will impact agricultural yields. The sum total of these interacting changes (land-use changes and changes in agricultural practices) will have environmental impacts. It is this portion of Figure 1, shown in green – “Reorganization of agricultural and forestry systems and spatial planning ➔ land-use change ➔ environmental impacts” – which constitutes the principal focus of the present study.

Several studies published at the end of the 2000s (Searchinger et al. 2008; Fargione et al. 2009; Wise et al. 2009) demonstrated that LUC could have a strong influence on environmental impact accounting. These early studies focused on a specific type of agricultural reorganization giving rise to LUC, the production of first-generation biofuels, and on a specific type of environmental impact, greenhouse gas emissions. Research since 2010 has examined a broader range of agricultural reorganization trends, LUC types, and environmental impacts. Agricultural reorganization trends considered by these more recent studies include changes in crop rotations, the intensification or extensification of cropping and/or livestock systems, new types of crops such as those used for second-generation biofuels (made from lignocellulosic biomass), the expansion of biologically based energies and materials, the expansion and contraction of livestock production, loss of agricultural land to urban development, and changes in dietary habits (see El Akkari et al., Chap. 2, in this volume for a complete analysis). All of these shifts can give rise to dLUC and/or iLUC. Some recent studies (van Vliet et al. 2016) consider not only the impacts on GHG emissions but also the impacts on soil, water quality, water availability, air quality, biodiversity, etc.

Over time, given a context of increased land requirements to meet global demand for food, energy, housing, and other infrastructure (UNEP 2014), environmental impact assessments of spatial planning should seek to account for the effects of land-use change in a more systematic way. The issue is gaining prominence within the articulation of public policy. Thus, recent proposals (European Commission 2016) for a revision of the Renewable Energy Directive (European Commission 2009) tend to emphasize and encourage the development of second-generation biofuels, which are considered to have a better environmental balance sheet because of their reduced impact on land use (Harris et al. 2015).

Published studies on LUC are extensive and diverse and at times yield contradictory findings. Thus, in De Cara et al. (2012), the range of variation of the GHG budget is wide, including both negative and positive values. To clarify public debate on the environmental impacts of LUC (both direct and indirect), as well as to contribute to the identification of relevant research questions, there is a need to synthesize the results of studies analyzing the effects of LUC on a broad range of environmental impacts. The specific goal is to be able to assign environmental impacts to agricultural reorganizations giving rise to LUC from the perspective of the causal chain described above. An analysis of the current literature on the subject shows, indeed, that the steps in this chain are typically viewed in isolation (van Vliet et al. 2016), impeding our ability to make connections between systemic reorganizations and environmental impacts.

## Organization and Objectives of This Special Volume

The goal of the study on which this special volume is based is thus to produce a systematic analysis of the international bibliography on the effects of different types of systemic reorganization (e.g., within agriculture, forestry, spatial planning) on land-use change and associated environmental impacts. It seeks to provide a “state of the research” on the topic in order to better characterize the magnitude of the phenomena involved and to identify emerging research questions. Our focus is on research published in scientific journals describing the totality of the causal chain “reorganization of agricultural and forestry systems or spatial planning ➔ land-use change ➔ environmental impacts.”

The first article in this volume describes the overall methodology employed, including how the boundaries for the systematic literature review were defined (Réchauchère et al., Chap. 1, this volume). Our review resulted in the identification of 5730 references, using a search equation combining keywords from the field of LUC and the field of environmental impact assessment. A textual analysis of this corpus was then conducted (El Akkari et al., Chap. 2, this volume), leading to the identification of major themes, emerging topics, and principal scientific methodologies employed.

A more in-depth analysis was then applied to a subgroup of the corpus made up of references examining shifts toward the production of nonfood biomass. The analysis was based on a systematic dissection of these references’ content using an analytical grid breaking down types of environmental impacts. Impacts on soil (Bessou, Chap. 4, this volume), water (Bispo, Chap. 5, this volume), climate (Bamière and Bellassen, Chap. 6, this volume), air quality and human health (Gabrielle, Chap. 7, this volume), biodiversity (Gaba, Chap. 8, this volume), and nonrenewable resources (Dumas, Chap. 9, this volume) are examined in the subsequent six articles. A further article (Gabrielle, Barbottin, and Wohlfahrt, Chap. 3, this volume) offers a transversal analysis of the links between systemic reorganization, land-use change, and environmental impacts and associated research methodologies.

The volume concludes with an article (Makowski, Chap. 10, this volume) using an “evidence mapping” methodology to represent in a summary and graphic form the major conclusions drawn from our analysis of the sub-corpus on “nonfood biomass.” This approach also assists in highlighting knowledge gaps and thus in identifying future research needs.

This study was funded by the Agency for Energy and the Environment (ADEME) and the Ministry of Agriculture and Forestry (contract no. 12-60-C0004). It was made possible by the work of Sophie Le Perchec (INRA Rennes), who completed the documentary research, as well as by the following researchers, who contributed to the detailed analysis of the articles: Laure Bamière (INRA Grignon), Aude Barbottin (INRA Grignon), Valentin Bellassen (INRA Dijon), Martial Bernoux (IRD Montpellier), Cécile Bessou (CIRAD Montpellier), Antonio Bispo (ADEME Angers), François Chiron (AgroParisTech, Orsay), Stéphane De Cara (INRA

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# Contents

# Chapter 1
# An Innovative Methodological Framework for Analyzing Existing Scientific Research on Land-Use Change and Associated Environmental Impacts

**Olivier Réchauchère, Monia EL Akkari, Sophie Le Perchec, David Makowski, Benoît Gabrielle, and Antonio Bispo**

**Abstract** This article describes an original approach to surveying and analyzing the existing body of scientific research on (1) the effects of various forms of reorganization in agriculture, forestry, and spatial planning on land-use change (LUC) and (2) the impacts of that LUC on the environment. Our approach consisted of four principal steps: (i) identification of references using a bibliographic search process; (ii) description of the references' key features (publication date, journal of publication, etc.); (iii) textual analysis of the articles and identification of thematic sub-groups; (iv) systematic examination of a subset of the corpus using an reading grid followed by an analysis of the results. Our findings show that the majority of publications relating to the environmental impacts of LUC were published after 2000, and amount to a corpus of more than 5700 articles. The scientific journals involved are diverse in nature, with some being general in focus and others more specialized and technical. A lexical analysis performed using the digital platform CorTexT, devel-

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oped by IFRIS (Institute for Research and Innovation in Society, a research consortium based in the Paris region. http://ifris.org/), enabled us to identify several themes within this corpus, in terms of both the types of reorganizations considered and the types of impacts examined. A more detailed analysis was conducted on a subset of articles dealing with the production of non-food biomass. The results show that, within this sub-group, the environmental impacts most often studied are those relating to climate, soil, and water. Our approach demonstrates the utility of textual analysis as a partially automated method for identifying, in broad outline, the topics addressed within a large-scale corpus. As with a search by keywords, however, this type of textual analysis cannot guarantee that all the articles classed within a category genuinely address the corresponding topic. Among those articles assigned by CorTexT to the sub-group on non-food biomass (1785 articles), the majority proved not relevant to our chosen topic, and only 241 articles were ultimately selected. This selection phase could not be fully automated and required a close reading of titles, abstracts, and often main texts by human experts. The use of precise criteria for selection and a formal reading grid are helpful in limiting the risk of bias and ensuring a level of transparence in the analytical process. Implementation of such an approach is time-consumptive, however, and requires considerable human effort.

**Keywords** Bibliometric · Textual analysis · Systematic review · Land-use change · Environmental impact

## 1.1 Introduction

Territorial reorganization, whether it pertains to agriculture, forestry, or other forms of land-use, can reflect a range of different logics and objectives: intensification, extensification, the expansion of livestock production, bioenergy development, new housing construction, other types of infrastructure development, etc. In many cases, these types of reorganization result in direct or indirect land-use change (LUC), the environmental impacts of which have only recently become a focus of scientific research (Veldkamp and Verburg 2004).

Early studies seeking to account for LUC within the context of environmental impact assessments were focused primarily on reorganizations in favor of the production of bio-energy. The production of non-food biomass has expanded considerably over the course of the last decade in response to increased investment in the "bio-sourced economy" (bio-energy, biomaterials, etc.), and this trend seems likely to continue over the near future as consumption of fossil-based resources diminishes (Chum et al. 2011). Concerns have been raised recently as to the consequences of LUC linked to the expansion of primary material production, notably in terms of the greenhouse gas impacts (Searchinger et al. 2008). Such concerns have prompted a sharp increase in the number of scientific publications on this topic over the past 10 years.

To account for LUC impacts within the environmental footprint of biomass production, and ultimately within the increased use of the end products of this biomass (e.g., biofuels), we need to be able to link changes in biomass production to changes in the use and management of soils, and then determine the impacts of those LUC on the environment. The goal is thus to describe a causal sequence in three steps: reorganizations in the production of primary materials; LUC (both direct and indirect) in response to these reorganizations; and a range of potential environmental impacts, including GHG emissions, atmospheric pollution, biodiversity impacts, water resources, and soil quality.

Although a number of recent studies have been published in this field (Berndes et al. 2013, Broch et al. 2013), none of these attempts a systematic literature review encompassing the full causal sequence, "reorganization – LUC – environmental impacts." Indeed, one recent review of the subject specifically highlighted this gap in the scientific literature on "land use" (van Vliet et al. 2016), pointing to a division between research focused on LUC drivers and those examining LUC impacts. Scientific research on LUC tends to be highly segmented. This is no doubt due in part to the effect of proactive public policies favoring specific value chains, creating a demand for specialized research. Case studies on the use of biofuels in the transport sector are an example of this (Liska and Perrin 2009).

The originality of our study lies in its effort to identify and characterize published scientific work describing the complete causal sequence, "reorganization – LUC – environmental impacts." Our objectives are to examine both the range of territorial reorganizations and the range of environmental impacts considered in the literature. The land-use categories accounted for in our study are those defined by the Intergovernmental Panel on Climate Change[1] (IPCC et al. 2006) – forest, arable crops, grasslands, wetlands, built-up areas – with the addition of a separate category for "perennial crops," which we felt was important within the context of this study since it enables us to separate out the lignocellulosic species used for the production of second-generation biofuels.

This article describes an original methodological framework for identifying and analyzing scientific research studying LUC impacts on the environment in conjunction with the territorial reorganizations giving rise to those LUC. Our procedure consisted of four principal steps: (i) identification of research articles using a bibliographic search process; (ii) description of these articles' principal characteristics; (iii) textual analysis of the articles and identification of thematic sub-groups; (iv) systematic closer examination of a subset of the corpus based on a reading grid and analysis of the results. To our knowledge, this is the first time this ensemble of approaches has been used together to assess the environmental impact of LUC, and specifically LUC linked non-food biomass production.

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[1] https://www.ipcc.ch/

## 1.2 Identification of Research Articles Using a Bibliographic Search Process

The objective was to inventory and analyze all existing articles that describe both (i) the effects of agricultural, forestry, and spatial planning reorganizations on land-use change (LUC) and (ii) the environmental impacts of those LUC. The basic principle was to search for all articles situated at the intersection of the two research areas of LUC and environmental assessment.

In Table 1.1, search request #3 defines the field of environmental assessment by crossing keywords adjacent to the concept of assessment (search request #2) with keywords relating to the environment (root term “environment*”). Keywords defining the field of LUC are then grouped into search request #9. To capture all articles likely to be relevant to our search target, however, simply crossing search request #3 with search request #9 is insufficient. Many studies in fact engage in environmental assessment without explicitly mentioning the term, particularly publications pertaining to life-cycle analysis (LCA) and greenhouse gas (GHG) emissions budgets, which were accordingly added to the search. Keywords relating to LCA (search

**Table 1.1** Details of the searches completed

| Search number | Search equation |
|---|---|
| #1 | TS=(life AND cycle) OR TS=lifecycle* OR TS=LCA OR TS=LCIA |
| #2 | TS=balance OR TS=Analysis OR TS=impact* OR TS=accounting* OR TS=assessment* OR TS=quality OR TS=performance* OR TS=equity OR TS=externalit* OR TS=sustainability OR TS=valuation OR TS=evaluation |
| #3 | TS = environment* AND #2 |
| #4 | #2 AND #1 |
| #5 | #3 OR #4 |
| #6 | TS = (“greenhouse gas*” OR ghg OR biofuel*) |
| #7 | #6 AND #2 |
| #8 | #7 OR #5 |
| #9 | TS=“landuse change*” OR TS=“land use change*” OR TS=“landuse allocation*” OR TS=“land use allocation*” OR TS=“landuse dynamic*” OR TS=“land use dynamic*” OR TS=“land use option*” OR TS=“landuse option*” OR TS=“land use transition*” OR TS=“landuse transition*” OR TS=“land use conversion*” OR TS=“landuse conversion*” OR TS=“land use competition*” OR TS=“landuse competition*” OR TS=“land use take*” OR TS=“landuse take*” OR TS=“land use conversion*” OR TS=“landuse conversion*” OR TS=“land use scenari*” OR TS=“Landuse scenari*” OR TS=“land use strateg*” OR TS=“Landuse strateg*” OR TS=“land use impact*” OR TS=“Landuse impact*” OR TS=“land use competition*” OR TS=“Landuse competition*” OR TS=“land use expansion*” OR TS=“Landuse expansion*” OR TS=“land grabbing” OR TS=“land sparring” OR TS=“Land sharing” OR TS=“agricultural expansion*” OR TS=“Marginal land*” OR TS=“land abandonment” |
| #10 | #8 AND #9 |

TS means “Topic.” Searches included the Web of Science™ fields for Title, Abstract, “Author keywords,” and “Keywords plus” request #1) were then crossed with the keywords for assessment (search request #2) to create search request #4; similarly, keywords relating to GHG (search request #6) were crossed with the keywords for assessment (search request #2) to create search request #7. Note that request #6, relating to GHG, was enlarged to include research on biofuels, based on the hypothesis that studies of biofuels often consider impacts in terms of GHG. Search request #3 (environmental assessment) was thus expanded through two further request sequences, first (request #5) by the addition of request #4 (LCA), then (request #8) by the addition of request #7 (GHG budgets). The equation thus generated was crossed with keywords for the field of LUC (request #9) to obtain the final search request (request #10). This search was performed in the Web of Science™ (WoS™, 2/4/15) resulting in the assembly of a corpus of 3500 references.

This corpus was supplemented by using the database CAB Abstracts (Centre for Agricultural Bioscience) to identify those articles present both in the CAB and in the WoS™ and which had missed being identified in the direct search of WoS™. In the CAB database, each article is re-indexed with a thesaurus for the keyword field (descriptor). Thanks to this systematic indexing process, we were able to submit our search request previously used in WoS™ to the CAB database as a way of uncovering any articles in the WoS™ that were potentially relevant to our study but had not been captured in the initial corpus of 3500 articles, either because of poor indexing based solely on the keywords supplied by the authors or because our search terms did not appear in the title or abstract.

This search strategy, in combination with an updating of the database to include any articles published since the initial request, enabled us to expand our initial corpus, arriving at a final corpus of 5730 references (as of February 4, 2015).

## 1.3 Description of Key Characteristics for the 5730 References

The distribution of references by year is presented in Figs. 1.1 and 1.2. This is a topic area that emerged relatively recently and is undergoing rapid development. The histogram in Fig. 1.1 offers a visual representation of the growth in the number of publications on this topic, which appears not to have been addressed in the scientific literature to any significant degree prior to the 1990s, with a clear acceleration in publication rates from 2007 on. The number of published articles has increased considerably from year to year, reaching 750 articles appearing in 2013.

To eliminate the effect of the increase in the total number of publications appearing in the WoS™ over this time period, we divided the number of articles referenced on the subject each year (as presented in Fig. 1.1) by the total number of references indexed in the WoS™ each year. The ratios thus obtained show the percentage of articles published on our topic each year. The resulting curve (Fig. 1.2) shows the change in this relationship over time.

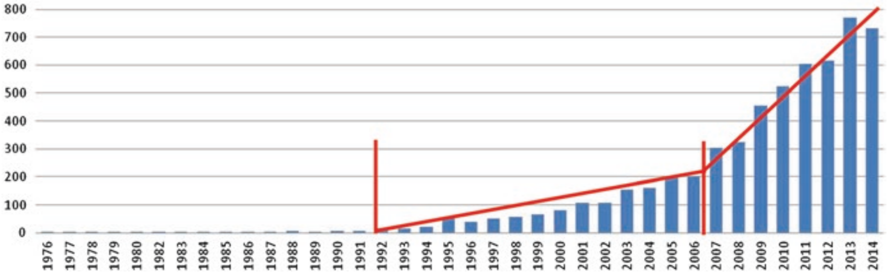

**Fig. 1.1** Histogram showing the distribution of publication date within the corpus of 5730 articles

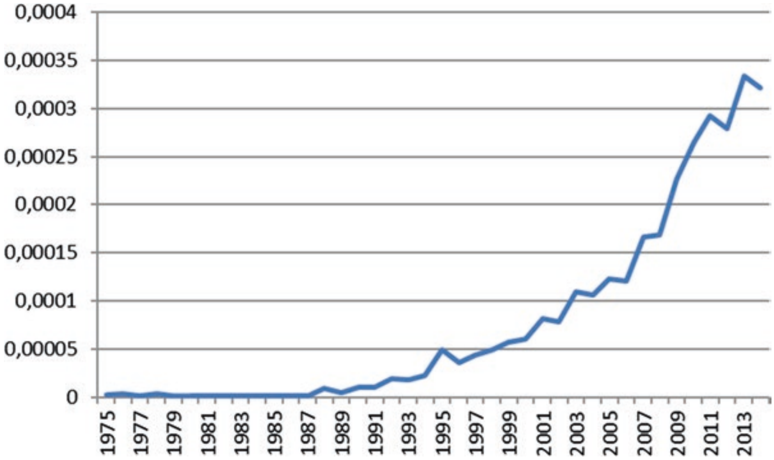

**Fig. 1.2** Line graph representing the number of publications within the corpus of 5730 articles per year divided by the total number of publications in the WoS™ per year

This graph shows that the increase in annual output of publications on our topic is not simply a result of the increase in the total volume of publications appearing in the WoS™ (which would produce a horizontal line). Rather, we can observe that since 1990, publications addressing the theme of our study account for an increasing percentage of materials indexed in the WoS™, with the percentage doubling approximately every 5 years. It is not possible to say at this time whether this trend will soon plateau or not.

The articles in our corpus have been published in a wide range of journals, more or less focused on the themes in question (Table 1.2). Included are generalist journals (e.g., *Plos One*, *Agriculture, Ecosystems & Environment*), journals focusing on environmental impacts (e.g., *Science of the Total Environment*, *Applied Geography*, *Environmental Research Letters*), and more specialized thematic journals (*Land Use Policy*, *Climatic Change*). The majority of articles in the corpus appeared in environmental journals, which give considerable attention to the "impacts" segment of our study area.

**Table 1.2 Journals most frequently represented** and number of articles identified for each journal (1976–2015)

| Journal | Number of **Articles** | Category |
|---|---|---|
| Agriculture Ecosystems & Environment | 128 | General |
| Land Use Policy | 125 | Thematic |
| Biomass & Bioenergy | 90 | Thematic |
| Global Change Biology | 82 | Impacts |
| Landscape and Urban Planning | 82 | Thematic |
| Environmental Management | 76 | Impacts |
| Journal of Environmental Management | 75 | Impacts |
| International Journal of Life Cycle Assessment | 70 | Impacts |
| Journal of Hydrology | 60 | Impacts |
| Environmental Monitoring and Assessment | 57 | Impacts |
| Plos One | 55 | General |
| Science of the Total Environment | 55 | Impacts |
| Ecological Modelling | 54 | Impacts |
| Environmental Science & Technology | 54 | Impacts |
| Global Change Biology Bioenergy | 53 | Thematic |
| Climatic Change | 50 | Thematic |
| Ecological Indicators | 49 | Impacts |
| Environmental Research Letters | 49 | Impacts |
| Ecological Economics | 48 | Thematic |
| Proceedings of the National Academy of Sciences of the United States of America | 47 | General |
| Energy Policy | 45 | Thematic |
| Applied Geography | 44 | Thematic |
| Catena | 43 | Thematic |
| Biological Conservation | 42 | Impacts |
| Journal of Cleaner Production | 41 | Impacts |
| Forest Ecology and Management | 41 | Impacts |
| Land Degradation & Development | 41 | Impacts |
| Ecological Applications | 41 | Impacts |
| Hydrological Processes | 40 | Impacts |
| Global Environmental Change-Human and Policy Dimensions | 40 | General |

Only those journals with more than 40 articles in the corpus are listed

## 1.4 Textual Analysis of Articles and Identification of Thematic Sub-groups

The corpus of 5730 articles was next analyzed using a textual analysis tool called CorTexT.[2] The full methodology and results of this analysis are described in the second article in this volume, and will thus not be reviewed in detail here.

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[2] CorTexT is a digital platform for textual analysis, developed by IFRIS (the Institute for Research and Innovation in Society, based in the Paris region). http://www.cortext.org/projects/cortext-manager

**Table 1.3** Keyword clusters developed by the textual analysis tool, with descriptions of their content

| Cluster title | Short description |
|---|---|
| Agricultural intensification, ecosystem services, landscapes, LUC and biodiversity | Cluster centered on biodiversity impacts, including keywords linked to the determinants of those impacts. |
| Agricultural practices, LUC and water resources (quantity and quality) | Cluster describing impacts on water and to a lesser extent on soils. |
| Climate change modeling and LUC | Cluster centered on climate change as an element of the general biophysical context |
| LUC and pasture systems | Cluster focused on grasslands management |
| Bio-energies, competition among feed/food/fuel crops, LUC and GHG accounting | Cluster organized around land reallocation for the production of biofuels, as linked to impacts on GHG emissions |
| LUC and carbon, $N_2O$ and $CH_4$ fluxes | Cluster describing GHG pools and fluxes |
| LUC and forest ecosystem management | Cluster focused on management of forest ecosystems (deforestation, reforestation, afforestation) |
| Socioeconomic determinants of LUC, urbanization and impacts on land use and spatial planning | Cluster linking a contextual element (land use policy) and a principal reorientation (urban expansion) |

The textual analysis is based on an automated search of titles, abstracts, and keywords for the selected references to produce a statistical analysis of the most frequently occurring terms and their proximity to one another within the articles (the idea of co-occurrence). The preferential association of certain keywords or terms leads to the identification of clusters of keywords. In our case, the textual analysis identified eight clusters (Table 1.3). Each cluster is characterized by keywords describing one or several types of land-use reorientation and associated environmental impacts.

Each cluster thus corresponds to a sub-group of articles that employ the keywords present in that cluster. In consultation with our study's advisory committee, the cluster relating to the production of non-food biomass was selected for further examination. This cluster corresponds to a group of 1785 articles. It should be noted that this includes some articles not limited to the single theme identified by the keywords present at the core of the cluster. Articles contributing to the identification of a cluster may also touch on other subjects.

## 1.5 Systematic Analysis of Articles in the "Non-food Biomass" Cluster

### *1.5.1 Article Selection*

The 1785 articles in the sub-corpus "non-food biomass," as identified with the assistance of CorTexT, proved to not all be relevant. The fact that an article contained keywords relative to non-food biomass production, LUC, and environmental

**Table 1.4** Criteria for article selection

| Categories retained | Selection criteria |
|---|---|
| **Definition of the concept of system reorganization** | Changes in land-use resulting in a change in land-use category (arable land, grasslands, forests, wild areas, urban areas); or within arable land areas, a change in crop use (food production, feed production, fuel production, etc.); as well as changes in agricultural practices (intensification, extensification, agroforestry) likely to lead to direct or indirect land-use change. |
| **Non-food biomass**<br>Types of biomass included | Energy biomass (wood, etc.)<br>By-products of annual crops (straw, stover), green wastes<br>Biofuels<br>Biomass grown for biogas production<br>Biomaterials (including wood pulp for paper production, materials for green chemistry…)<br>Livestock effluents<br>Recyclable municipal or industrial wastes (waste oils, etc.) |
| **Changes in land use** | Direct and indirect |
| **Environmental impacts:** | |
| On water | Qualitative (pollution, eutrophication, nutrient cycling); quantitative (flooding, water scarcity) |
| On air or climate | Direct pollution of ambient air, greenhouse gas emissions |
| On soils | Soil sealing, urbanization; degradation; erosion; loss of fertility in its physical, chemical, or biological components; reduction in organic matter levels |
| On biodiversity or landscapes | Species abundance, species richness<br>Species studied<br>Habitats<br>Landscape |
| On plant or animal health | No specific criteria |
| On human health | Pollution, allergens, diseases, parasites |

impacts did not guarantee that the article indeed described the impact of reorganizations within the agricultural and forestry sectors on LUC and the impacts of these LUC on the environment.

A selection process was therefore implemented whereby a group of 22 experts in the relevant fields reviewed the titles and, if necessary, the abstracts of the articles in order to determine their relevance to the theme in question.

After testing the selection process on a sample of articles, the references were divided up randomly among the experts in the working group, with 200 articles assigned to each expert. Precise selection criteria were provided for the experts' use (see Table 1.4).

Following this selection process, 614 articles out of the 1785 selected by CorTexT were retained, or about a third of the initial total. Many articles in fact only addressed a portion of the essential causal sequence that formed the focus of our study: some studied the effect of reorganizations on LUC without considering the resulting environmental impacts; others focused only on the environmental impacts of LUC in general without describing the circumstances giving rise to those LUC.

### 1.5.2 Development of a Reading Grid and Detailed Analysis of the Selected Articles

A reading grid was then developed to extract the key information contained in the 614 selected articles. The grid consisted of three series of rubrics corresponding to the three steps in the causal sequence "reorganizations/LUC/environmental impacts." The approach to constructing the grid (see Annex) was to list the central qualitative descriptors for each type of reorientation (new crops or livestock introduced, change in cropping practices, land area, location, etc.), for the LUC (direct, indirect, location, land-use types affected, etc.), and for the impacts (water, air, soil, climate, etc.). The resulting form included several multiple-choice questions and a few open-ended questions. These first-order descriptors were complemented by further descriptors seeking to characterize the articles' research methodology, the type of data examined, the accessibility of the results, and the precision of the estimates – the last three items helping to determine whether the article could be a candidate for further statistical analysis (meta-analysis). Additional blank fields were included in the grid so readers could record further information if desired. The grid was tested by the experts on a few articles in order to refine its format and validate its use.

The articles were divided up among the experts, respecting as much as possible a policy of aligning the researcher's area of expertise with the focus of the article (notably with respect to the type of territorial reorientation and the type of environmental impact). Each expert received between 30 and 40 articles to study in depth. Since the object of our study was to conduct a literature review, "review"-type articles were excluded. Including them would have given undue weight to the research articles included in the review articles where these were also present in the corpus, or, where they were not, would have introduced into the analysis information from primary articles not represented in our corpus.

In this step, information from 241 articles (out of 614) was extracted using our analytical grid. Detailed reading of these articles showed that nearly two out of three did not correspond to the selection criteria. Again, the principal motivating factor for rejecting an article was if it did not address the full causal chain of reorientation/LUC/environmental impacts. It was not possible to make this determination based on a review of titles and abstracts alone.

Our reading of the 241 articles revealed that their principal objective was, in most cases, the assessment of the environmental impacts of LUC. Analysis using the reading grid made it possible to count the number of articles relating to each category of impact (Fig. 1.3). Ten impact categories were distinguished: impacts on soil; on water; on air; on biodiversity; on landscapes; on plant or animal health; on human health; on climate; on non-renewable resource depletion; and on waste production. Several of these categories were then combined to yield a smaller number of groups: impacts on plant and animal health were combined with impacts on landscapes and biodiversity; impacts on air were combined with impacts on human health. Finally, the two articles on waste output were excluded, reducing the number of categories to six. The 241 articles were then allocated to the six categories. The

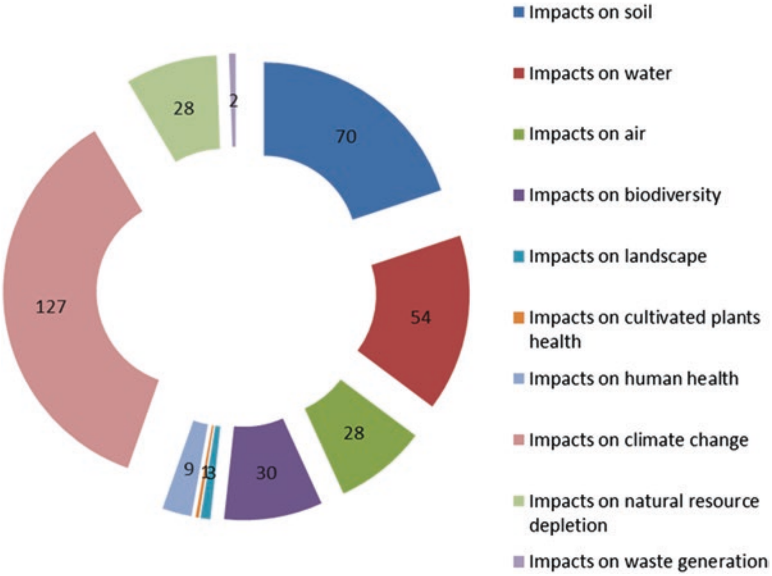

**Fig. 1.3** Distribution of the selected articles following systematic analysis by impact category. The total number of articles exceeds 241 since some articles address several types of impacts

most frequently studied impacts were impacts on climate, soil, and water (Fig. 1.3). The articles in each category were divided among groups of 1–3 experts, who then summarized their content. The results of these summaries are presented in the subsequent articles in this volume.

## 1.6 Conclusion

The methodology presented in this article is based on a step-by-step sorting and selection of articles, beginning with a large number of references initially identified using a bibliographic search of the Web of Science™ database. Each selection step was formalized as carefully as possible in order to avoid selection bias by the expert group, generally expressed by the fact that researchers have a tendency to overvalue references relating more directly to their own area of research, and to undervalue references outside their own area of expertise. The key steps in our selection procedure are summarized in Fig. 1.4. Our results show that the links between territorial reorganizations and LUC and between LUC and environmental impacts have been the focus of considerable scientific research, and that published studies have appeared for the most part since 2000. The scientific journals involved are highly diverse, with some being very general in focus and others more specialized and

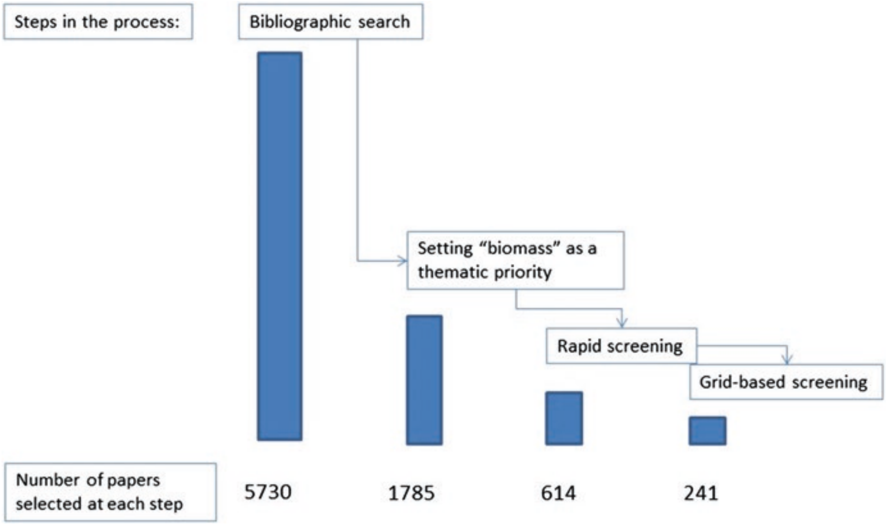

**Fig. 1.4** Steps in the process of article selection and analysis

technical. Closer analysis was made of a subset of the corpus focused on the production of non-food biomass. Within this sub-group, we determined that the most frequently studied environmental impacts were those related to climate, soil, and water.

Our approach in this study demonstrates the utility of textual analysis using CorTexT as a partially automated method for identifying, in broad outline, the themes addressed within a large-scale scientific corpus. As is true for searches by keywords, however, textual analysis cannot guarantee that all the articles classed in a category genuinely address the theme corresponding to that category. Among the articles classed by CorTexT into the sub-group on non-food biomass, the majority proved not to be relevant to our study objectives. In practice, article selection could not be fully automated, but rather required a careful reading of titles, abstracts, and often the body of the text by human experts. The use of precise selection criteria and a formal reading grid can assist in limiting the risk of bias and ensuring a level of transparency for the process of article analysis. The application of such a methodology is time-consuming, however, and requires considerable human investment.

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# Chapter 2
# Textual Analysis of Published Research Articles on the Environmental Impacts of Land-Use Change

**Monia EL Akkari, Mélanie Sandoval, Sophie Le Perchec, and Olivier Réchauchère**

**Abstract** Regardless of the scale considered, land use is determined by a variety of factors relating to both local soil and climatic conditions and socioeconomic considerations (population growth, food and energy requirements, public policies, etc.). Changes in land use resulting from shifts in these factors over time will have environmental consequences. We conducted a review of the scientific literature to identify the degree to which environmental assessments take direct and indirect land-use change into account. A textual analysis was completed on a collection of 5730 scientific articles, published between 1975 and 2015 and listed in the WoS™ database, addressing the relationship between reorganizations of agricultural and forestry systems, or spatial planning, direct and indirect land-use change resulting from these reorganizations; and environmental impacts. By identifying the most frequently used words or groups of words within this corpus (focusing on the title, abstract, and keywords fields), the textual analysis platform CorTexT Manager (Platform developed by IFRIS (the Institute for Research and Innovation in Society, based in the Paris region) assembles diagrams, or "maps," of occurrence and co-occurrence for these terms, which can then be used to identify the principal themes addressed in the corpus based on clusters of proximate keywords. Eight clusters were so identified: two focused on climate change and greenhouse gas fluxes in terrestrial ecosystems (thus corresponding both to an aspect of the biophysical context and an environ-

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mental impact linked to a reorganization); one associated a reorganization (biofuel production) with a dominant environmental impact (the effects of greenhouse gas emissions); three were centered on keywords related to other types of reorganizations (urbanization, grassland management, forestry management); and two focused on environmental impacts on biodiversity and water resources. The five "thematic identifiers" showing the highest number of occurrences were *greenhouse gas emission*, *land-use policy*, *biofuel*, *farm system*, and *pasture land*, suggesting that the theme "GHG impacts of biofuel production" is the most prevalent. A more detailed textual analysis of articles in the cluster relating to non-food biomass production (1785 articles) was also conducted, and confirmed the growing importance, notably since 2005–2006, of research linking the bioenergy production, land-use change, and climate impacts from greenhouse gas emissions. Reorganizations toward non-food biomass production also help explain the presence of degraded lands among the most frequently occurring terms in the corpus. Life-cycle analysis is the most important assessment methodology used to evaluate the environmental impacts of bioenergy production.

**Keywords** Textual analysis methodology · Cortext · Land-use change · Bioenergy

## 2.1 Introduction

Reorganizations of agriculture, forestry systems, or spatial planning have a range of environmental impacts, some of which relate to direct or indirect land-use changes triggered by these reorganizations. Research seeking to account for such impacts is relatively new in the scientific literature (Searchinger et al. 2008). It has become commonplace in studies of bioenergy production (De Cara et al. 2012), but could potentially be applied to all types of agricultural reorganization (intensification, extensification, expansion of livestock production, etc.) or more generally to any reorganization affecting land use (urbanization, afforestation, etc.). Given the recent emergence of this type of approach (Réchauchère et al., this volume), it is difficult to obtain a overall view of the range of reorganizations and categories of environmental impact that have been most widely studied.

Our use of a textual analysis methodology thus sought to explore how this research area has evolved since the earliest studies seeking to account for the environmental impacts of LUC – that is, those focused on GHG assessments of crop production for bioenergy, usually by way of life-cycle analysis (LCA). Our approach is exploratory, but also seeks to test a number of hypotheses with regard to a handful of emerging topics: Are other types of reorganizations being examined, such as the introduction of lignocellulosic crops for bioenergy or biomaterials, the modification of cropping and livestock systems (intensification/extensification), or the growth of urban areas? How common are studies of indirect LUC? Are studies of environmental impacts other than those linked to GHG emissions becoming more frequent (e.g., impacts on water, soils, biodiversity)?

Textual analysis *via* the automated exploration of a corpus, without any preconceptions as to its content, would appear to be a useful method for rapidly obtaining an overall understanding of the content of a collection of articles. We applied this approach to a group of 5730 articles selected by means of a systematic bibliographic search. Our search equation was intended to select articles at the intersection of the fields of environmental assessment and land-use change (LUC), as described in more detail in the previous article in this issue (Réchauchère et al., Chap. 1, this volume). The results from the textual analysis are used to reveal, in visual form, the principal themes addressed within articles studying the environmental impacts of land-use change.

## 2.2 Textual Analysis Methodology

### *2.2.1 Key Steps in Textual Analysis*

Literature analyses of relatively large fields of knowledge, as is the case for this study, are confronted with the challenge of reviewing several thousand or even tens of thousands of articles. Textual analysis software to perform an automated examination of the corpus offers a way to rapidly explore the literature to obtain a preliminary idea of the themes addressed and the relationships that exist between those themes. Several recent studies demonstrate the value of textual analysis for exploratory investigation of a subject area (Reboud et al. 2012; Tancoigne et al. 2014; Sandoval and Tarot 2014).

Textual analysis consists of two principal steps. The objective in the first step is to identify the most important words or groups of words (terms) within the articles (title and abstract or full text) and to calculate their frequency in the overall corpus. Words without specific meaning (conjunctions, words present in all scientific articles) are eliminated. Synonymous words or terms are combined, and then an index of terms, accompanied by their frequency of occurrence in the corpus, is generated.

The objective in the second step of textual analysis is to calculate the frequency of co-occurrences of the terms in the index – that is, the frequency at which two terms are found within the same article. Co-occurrence maps are then created to present the results in a summary form. These maps provide a visual representation of the topics addressed in the corpus. These “visualizations” make it possible to assess which keywords appear most frequently, and which appear most frequently together, by arranging them into groups of related keywords, known as clusters. Analyzing the terms and the relationships between the terms within a cluster makes it possible to identify a theme specific to that group of articles. Relationships between clusters can highlight how the different themes present in the corpus interrelate.

For this study, we used the textual analysis program CorTexT Manager. This digital textual analysis platform was developed by IFRIS (the Institute for Research and Innovation in Society), a research consortium in the Parisian region. CorTexT Manager makes it possible to conduct large-scale literature reviews and to correlate large volumes of data.

### 2.2.2 Step One of Textual Analysis: Defining an Index of Terms

The textual analysis operation was applied to a corpus of 5730 references extracted from the Web of Science™ database (WoS™) for the period 1976–2015 (see Réchauchère et al., Chap. 1, this volume). Exploration of the corpus was focused on the keyword, title, and abstract fields. Expanding the analysis beyond the keywords assists in gathering the maximum number of relevant terms, notably those present in the article abstracts, rather than restricting oneself to those aspects of the study highlighted by the authors in their choice of keywords.

The extraction of terms is performed by the software based on a calculation of the frequency of:

- groups of words (multi-word terms): the software selects the nominal groups that recur most often
- single-word terms (monograms).

After a calibration procedure, the CorTexT Manager program will automatically group allied terms (e.g., singular and plural versions of the same word), as well as eliminating "meaningless" words (and, but, or, etc.) as listed in a dictionary contained within the program. Taking multi-terms and monograms together, we limited the study to the most frequently used 2000 terms. This threshold corresponds to a maximum above which handling and direct analysis of the extracted terms becomes unmanageable (particularly with regard to the manual regroupings). We can however confirm that this threshold of 2000 terms is methodologically acceptable, as all the eliminated terms had an occurrence of two or less.

This series of 2000 terms was then winnowed down, first by eliminating words that were unrelated to the study or that were not meaningful in themselves ("year," "time"). Next, a decision was made to assemble a small, multi-disciplinary group of researchers with expertise corresponding to the different aspects of our study: biofuels; livestock production; forest ecosystems; soils and agronomy; biodiversity. The experts grouped terms they considered to be synonymous or to correspond to a single subject or concept (Table 2.1). Creating groupings in this way makes it possible (1) to avoid redundancy and to give just weight to an ensemble of terms with the same meaning, and (2) to render other, less frequent terms visible on the map, rather than having these be masked by the presence of large numbers of synonymous terms. Topic maps can only show a limited number of terms – approximately 200 – if they are to remain legible. A **thematic identifier**, i.e. a meaningful tag (also known as the "main form") is assigned by the user to each of these groupings.

In addition, all terms related to land-use change, whether direct or indirect ("Land use," "land-use change," "land-use expansion," "land grabbing") (see Article 1), were hidden, again so as to suppress their appearance on the topic map and thus render visible other terms appearing less frequently in the corpus without exceeding the threshold of 200 terms displayed. Since land-use change is the common denominator for all the articles, including it on the map would not provide additional useful information in this phase of the study.

**Table 2.1** Sample of the index created using the most frequent terms within the 5730 articles

<table>
<tr><th>Main form (thematic identifier)</th><th>primary forms (terms present in the corpus and combined automatically or manually under the same thematic identifier)</th></tr>
<tr><td>Acidification</td><td>Acidification and eutrophication|&|eutrophication and acidification|&|ocean acidification|&|acidification</td></tr>
<tr><td>Aerial photos</td><td>Aerial photos|&|aerial photographs|&|aerial photographs|&|satellite data|&|satellite images|&|satellite image|&|multi-temporal satellite imagery</td></tr>
<tr><td>Agricultural land expansion</td><td>Rapid expansion|&|agricultural expansion|&|crop expansion|&|crops expansion|&|expansion of this crop|&|future expansion|&|area expansion|&|expansion area|&|agricultural land expansion|&|land for agricultural expansion|&|cropland expansion|&|expansion of cropland|&|expansion of croplands|&|land expansion|&|expansion of land</td></tr>
<tr><td>Agroforestry</td><td>Traditional agroforestry practices|&|agroforestry practices|&|agroforestry systems|&|agroforestry system|&|agroforest|&|agroforestry|&|agroforestry practices|&|agroforests|&|orchard|&|orchards|&|faederbia</td></tr>
<tr><td>Bioenergy</td><td>Bioenergy potential|&|bioenergy potentials|&|bioenergy plantations|&|perennial bioenergy crops|&|bioenergy crops|&|bioenergy crop|&|bioenergy from crops|&|bioenergy feedstocks|&|bioenergy feedstock|&|bioenergy crop production|&|bioenergy development|&|bioenergy production|&|production of bioenergy|&|energy crop production|&|biomass for energy production|&|production of biomass for energy|&|dedicated energy crops|&|energy plants|&|energy crops|&|energy crop|&|energy generation|&|generation energy|&|perennial energy crops|&|bioenergy|&|bio-energy</td></tr>
</table>

Based on the terms obtained with the use of CorTexT and as refined by the scientific experts, an index made up of 1331 thematic identifiers was arrived at.

### 2.2.3 Step Two: Visualizing Thematic Identifier Occurrence and Co-occurrence

For each thematic identifier (see Table 2.2), CorTexT calculates a variable called *number of occurrences*, and then creates a map representing the corpus. The map shows, in graphic form, occurrences and co-occurrences for the 1331 thematic identifiers listed in the index. The thematic identifiers displayed on the map are those with the highest number of occurrences. The number of thematic identifiers shown on a map (150 or 200) is determined by the user so as to maximize the map's legibility.

Figure 2.1 shows a detail of a map obtained using CorTexT (included here solely to help explain how the program constructs this type of representation). The thematic identifiers from the index appear here as triangles, the size of which depends on the total number of co-occurrences they have with other thematic identifiers. The thickness of the lines between thematic identifiers indicates the strength of their connection (with line thickness being proportional to the frequency of co-occurrence of two identifiers within a single article). The threshold below which a line of co-occurrence is not shown is calculated automatically by CorTexT so as to

**Table 2.2** Principal thematic identifiers (IT) appearing in the index with >500 occurrences (excluding those related to land-use change)

| Thematic identifier | Identifier category | Nb occ |
|---|---|---|
| GHG emission | Reorganization | 3017 |
| Land use policy | Context | 2474 |
| Biofuel | Reorganization | 2462 |
| Farm system | Reorganization | 2186 |
| Pasture land | Reorganization | 1990 |
| Urban development | Reorganization | 1583 |
| Impact on biodiversity | Impact | 1576 |
| Erosion and soil degradation | Impact | 1343 |
| Landscape | Reorganization & impact | 1327 |
| LCA | Method | 1312 |
| Bioenergy | Reorganization | 1183 |
| Deforestation | Reorganization | 1165 |
| Climate change | Context & impact | 1156 |
| Soil carbon stock | Impact | 1136 |
| Carbon | Impact | 1114 |
| Degraded land | Context & impact | 991 |
| Habitat | Impact | 948 |
| Environmental impacts | Impact | 941 |
| Ecosystem service valuation | Method | 941 |
| Indicators | Method | 907 |
| Energy | Reorganization | 906 |
| Spatial approach | Method | 818 |
| Species | Impact | 801 |
| Climate change impact | Impact | 778 |
| Terrestrial carbon sequestration | Impact | 762 |
| Scenario uncertainty | Method | 728 |
| Benefits | Impact | 727 |
| Ground water | Impact | 648 |
| Reforestation and afforestation | Reorganization | 644 |
| Emissions | Impact | 632 |
| Nutrients | Impact | 622 |
| Water resources | Impact | 586 |
| Temperature change | Context & impact | 552 |
| Soil fertility | Impact | 543 |
| Sustainable production | Reorganization | 527 |
| Drivers | Context | 521 |
| Technology | Context | 513 |

eliminate the least frequent links and thus maintain legibility of the map. CorTexT likewise positions thematic identifiers within the map so as to minimize the distance between identifiers with the highest number of crossing co-occurrences. These groupings thus form clusters that are highlighted by a circle of color. The perimeter of the clusters is defined using the Louvain algorithm.

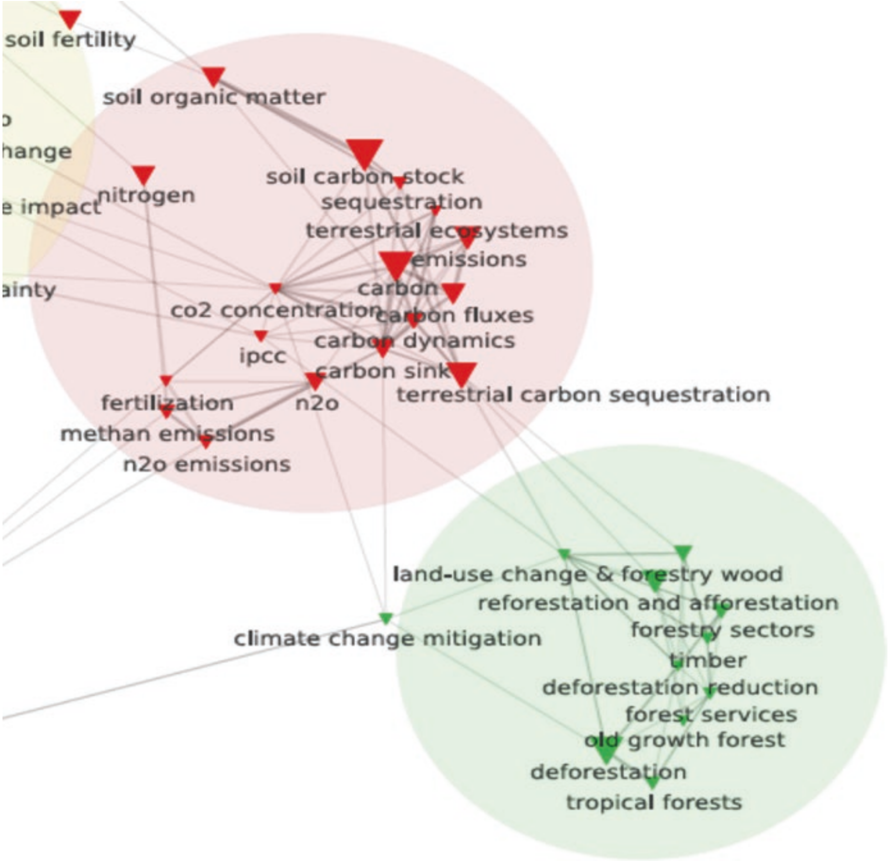


**Fig. 2.1** Detail of a visualization created by CorTexT. The visualization is a mapping of the network of connections among thematic identifiers

In this type of map, links between thematic identifiers (representing their co-occurrences) are only shown if they exceed a certain threshold of co-occurrence frequency, as determined by the user. Moreover, the number of nodes a thematic identifier can be linked to is limited to five. These filters improve the legibility and interpretability of the visualization.

### *2.2.4 The Limits of CorTexT and of Textual Analysis in General*

CorTexT has a number of limitations. Among these is the fact that the maps are sensitive to the relative weight of the different thematic identifiers, and thus to the identifier-grouping procedure, part of which is done manually. Maps will vary depending on whether the groupings are large or small, partially impacting the robustness of the results. Grouping decisions are based on expert knowledge that will implicitly or explicitly take into consideration the hypotheses underlying the decision to use textual analysis. Thus, while the textual data are handled by the CorTexT tool using "objective" statistical methods, the experts' role in the grouping phase introduces a subjective element that must be acknowledged. Another issue is that the maps are two dimensional, but the underlying calculations are made in three dimensions. When these are projected onto a two-dimensional plane, it can create artificial proximities between different clusters that can be difficult to interpret. In general, CorTexT can only document the co-occurrence of certain terms, without assigning meaning to those terms. It is thus useful for identifying major themes, but can do no more than generate hypotheses as to how the scientific literature approaches those themes.

## 2.3 Analysis of the Full Corpus (5730 References)

### *2.3.1 Analysis of the Principal Thematic Identifiers Extracted by CorTexT*

Among the 37 thematic identifiers appearing most frequently in the corpus (more than 500 occurrences; see Table 2.2), 9 relate to reorganizations (*biofuel, farm system, urban development,* etc.) and 17 to environmental impacts (*GHG emissions, impact on biodiversity*, *erosion and soil degradation*). Determining factors leading to reorganizations are also represented (*land-use policy*), as are methodologies (*LCA, ecosystem service valuation,* etc.) (Table 2.2). Some thematic identifiers could be assigned to multiple categories: climate change, for example, can be regarded both as a determining factor in system reorganization and as an environmental impact resulting from a reorganization.

With respect to the reorganizations themselves, we find identifiers related to energy production (*biofuel, bioenergy, energy*), forestry management (*deforestation, reforestation, afforestation*), and urbanization (*urban development*). Other thematic identifiers are more generic in nature, describing either the scale of the reorganization (*farm system, landscape*), or a qualitative characteristic of the reorganization (*sustainable production*).

With respect to environmental impacts, the various dimensions of the ecosystem are represented: the atmosphere, soils, water, biological communities; together with issues relating to changes in biodiversity, soil degradation/soil fertility, management of water resources, and GHG emissions.

This analysis of the frequency of the principal thematic identifiers give us an initial idea of the corpus's content, but it does not tell us anything about the relationships among these thematic identifiers.

### 2.3.2 Analysis of Thematic Identifier Co-occurrence

The map of the articles' content is presented in Fig. 2.2. Technically, this visualization is not based on *a priori* hypotheses (presented above in the introduction), although the groupings effected by the experts and the map description, particularly the titles assigned to the clusters, do take these hypotheses into account. The map enables us to identify research areas (as defined by the thematic identifiers) showing a high degree of co-occurrence, appearing on the map in the form of clusters. Clusters can bring together contextual elements, types of reorganization, impacts, and methods; or they may be focused on just one of these dimensions. Our expert group was next asked to interpret these groups of identifiers. The map also makes it possible to study the links between the clusters, reflecting the relationships between the various thematic identifiers.

Although this type of representation of a corpus does not require the formulation of prior hypotheses, it does make it possible to evaluate hypotheses in light of a graphic representation of the structure of a field of scientific inquiry. It is a descriptive approach, similar to principal component analysis (PCA) or correspondence factor analysis (CFA), etc., in the sense that it does not rely on the testing of a hypothesis with a probabilistic model. The links among the keywords and the themes appearing on the map are correlations, useful in helping to form hypotheses, but should not be understood as causal relationships.

Using this map, eight groups of preferential co-occurrences were identified (Fig. 2.2). Closer study of the thematic identifiers making up those eight groups enables us to give each one a title and to characterize the theme it addresses (see Table 2.3). The assigned titles associate the key thematic identifier with a reference to the causal sequence that is the focus of our study ("reorganizations/LUC/impacts"), since in most cases one or two terms in this sequence are predominant within the cluster.

1. Agricultural intensification, ecosystem services, landscapes, LUC and biodiversity,
2. Agricultural practices, LUC and degradation of soil and water resources (quantity and quality),
3. Climate change modeling and LUC,
4. LUC and pasture lands,
5. Bioenergy, feed/food/fuel competition, LUC and greenhouse gas assessments,
6. LUC and carbon, $N_2O$, and $CH_4$ fluxes,
7. LUC and management of forest ecosystems,
8. Socioeconomic determinants of LUC, urbanization, spatial planning and impacts on soils.

This step of assigning titles to the clusters is central to the methodology, and requires a detailed description. Two initial points should be made:

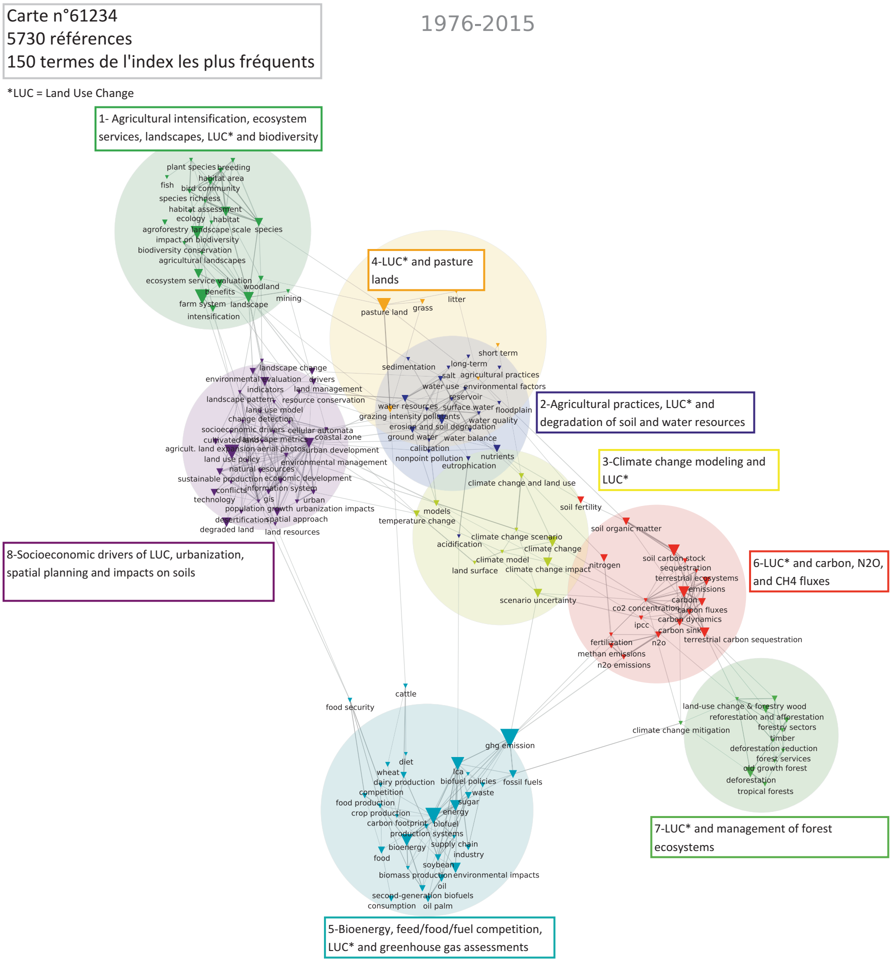


**Fig. 2.2** Overall map of the full corpus of 5730 articles (*LUC: land-use change)

- All of the clusters implicitly include the theme of LUC (land-use change). Thematic identifiers describing LUC were intentionally removed from the map in order to allow other thematic identifiers to appear: elements prior to LUC in the causal sequence, including socioeconomic and biophysical factors giving rise to reorganizations, and different types of reorganization; elements following LUC in the causal chain, including different types of environmental impacts. The term LUC was accordingly included in all eight cluster titles, even though the LUC thematic identifiers are absent from the clusters.
- In describing each cluster, it is useful at the same time to explore the links existing between them. This can improve our ability to describe the logic of each cluster as well as help us better understand the structure of this field of research: for example, some clusters centered on a reorganization may be preferentially linked to a cluster describing a specific type of impact.

**Table 2.3** Major themes addressed in the eight clusters of the overall map. Thematic identifiers are assigned to one of three categories: context, reorganizations, impacts

| Cluster # | Context | Reorganizations | Impacts | Connection to other clusters |
|---|---|---|---|---|
| 3 | **« climate change »**<br>« climate models »<br>« climate scenarios » | | | Cluster 6<br>Cluster 2 |
| 8 | « Land use policy »<br>« population growth »<br>« socioeconomic drivers » | **« urban development »** | « degraded land » | Cluster 1<br>Cluster 2 |
| 5 | « diet »<br>« food security »<br>« food production »<br>« biofuels policy » | **« bioenergy »**<br>**« biofuels »**<br>« second generation biofuels »<br>« energy » | « GHG emissions »<br>« carbon footprint »<br>« diet »<br>« food security”<br>« food production » | Cluster 6<br>Cluster 8 |
| 7 | | **« deforestation »**<br>**« reforestation »**<br>**« afforestation »** | « climate change mitigation » | Cluster 5<br>Cluster 6 |
| 4 | | **« pasture land »**<br>« grass »<br>« grazing intensity » | | Cluster 5<br>Cluster 1<br>Cluster 2 |
| 1 | | « farming systems »<br>« intensification » | **« impact on biodiversity »**<br>**« ecosystem services valuation »** | Cluster 4<br>Cluster 8 |
| 6 | « IPCC » | **« terrestrial carbon sequestration »** | « soil carbon stock »<br>« methane emission »<br>« $N_2O$ emission »<br>« $CO_2$ concentration »<br>« carbon fluxes » | Cluster 7<br>Cluster 5<br>Cluster 4<br>Cluster 3 |
| 2 | | | **« water quality »**<br>« non-point pollution »<br>« eutrophication »<br>**« water balance »**<br>« water resources »<br>« water use »<br>**« erosion and soil degradation »** | Cluster 8<br>Cluster 5<br>Cluster 3 |

Description of the clusters is undertaken sequentially, beginning with those related primarily to “reorganizations and their determinants” and continuing with those related primarily to “impacts,” in accordance with the relational sequence forming the focus of our study (reorganization/LUC/impacts).

Cluster #3 relates to the study of climate change as an element of the general biophysical context, with thematic identifiers (TI) relating to climate change assessments of the "climate change scenario" and "climate model" types, or those leading to reorganizations and LUC (TI "climate change and land use," see Table 2.3). This cluster is closely linked to two other clusters relating to impacts: impacts on carbon, $N_2O$, and $CH_4$ fluxes (cluster #6); impacts on water resources (cluster #2).

Cluster #8, entitled "socioeconomic determinants of LUC, urbanization, and impacts of spatial planning on soils" is characterized by a large number of thematic identifiers, suggesting the complexity of this thematic (see Table 2.3), as well as the multi-disciplinarity nature of the theme. The most common identifier in this cluster is "land use policy," closely associated with the identifier "urban development." The cluster is thus polarized around a link between an aspect of the socioeconomic context and a type of land-use reorganization of agricultural systems. It also includes a primary environmental impact, expressed by the identifier "degraded land." The cluster is also strongly linked to other two clusters related to environmental impacts: cluster #1 (biodiversity impacts) and cluster #2 (impacts on soil and water resources). In terms of methodologies, tools for spatial analysis predominate (GIS, aerial photos, etc.).

Cluster #5, entitled "bioenergies, feed/food/fuel competition, LUC and greenhouse gases," is centered around reorganizations linked to biofuel production (see Table 2.3). Here we find TIs on "energy," "bioenergy," "biofuels," and "second-generation biofuels." This reorganization is tightly linked within the cluster to one major impact, greenhouse gas emissions, expressed in the TIs "carbon footprint" and above all "GHG emissions." The latter is strongly connected to cluster #6, detailing the major GHG fluxes ($CO_2$, $N_2O$, $NH_4$) and the resulting C pools evolution. Finally, this cluster includes a number of identifiers related to food, such as "diet," "food security," and "food production," inviting us to hypothesize a form of competition between food and non-food biomass consumption, although at this stage it is impossible to say whether this competition is simply cited in the articles as a concern that exists with respect to bioenergy production or if impacts on food security are genuinely examined as an aspect of reorganizations toward bioenergy. We can also note that this cluster is linked to the urbanization cluster *via* the thematic identifier "food security." Food security acts as a key linkage point between publications related to urbanization *via* its co-occurrence with the TI "population growth" and publications related to bioenergy *via* its association with the TIs "food" and "competition." The contextual element of "biofuels policy" is likewise present in the cluster. In terms of methods, unsurprisingly, life-cycle analyses are those that appear most often (TI "LCA").

Cluster #7, titled "LUC and management of forest ecosystems," relates to reorganizations of forestry systems and is split between deforestation (TI "deforestation") and reforestation (TI "reforestation and afforestation"). This cluster is strongly linked to cluster #6, describing impacts in terms of carbon fluxes and GHG, and to cluster #5, describing relationships between bioenergy, LUC, and GHG emissions. At the intersection of clusters #7 and #5, moreover, we find the TI "climate change mitigation," which probably corresponds to studies evaluating the potential role of forestry management and bioenergy in mitigating climate change.

Cluster #4, entitled “LUC and pasture,” represents a large number of publications. It includes only a few thematic identifiers, and these clearly anchor the cluster within the study of reorganizations: “grass,” “grazing intensity,” and “pasture land” (see Table 2.3). There is a strong consensus with respect to keywords among the authors of this group of publications. “Pasture land” is the most common TI within the cluster. It connects it to other clusters, including the bioenergies cluster *via* the thematic identifier “cattle;” and the impacts on biodiversity cluster, where there is a co-occurrence with the thematic identifier “species.” The TI “grazing intensity” links cluster #4 to cluster #2, relating to water and soil degradation.

Cluster #1, entitled “intensification, ecosystem services, landscape, LUC and biodiversity,” is centered on biodiversity impacts (TI “impact on biodiversity,” along with a series of related TIs), and less directly on the TI “ecosystem services valuation” (see Table 2.3). The reorganizations most strongly linked to this impact within the cluster are the intensification of agricultural practices (TI “farming systems” and “intensification”); outside the cluster, we can observe linkages to pasture practices (cluster #4) and especially urban development (cluster #8). Also present in this cluster is a thematic identifier relating to mining activities (TI “mining”). This reorganization is not represented by an independent cluster, given the small number of publications. However, the fact that it appears on the map suggests its importance for land-use change and biodiversity impacts in particular.

Cluster #6, entitled “LUC and fluxes of carbon, $N_2O$, and $CH_4$” is primarily centered on the description of carbon fluxes and carbon pools, and to a much lesser degree on fluxes of the two other GHG, methane and $N_2O$ (see Table 2.3). This cluster functions first of all as a cluster of impacts in terms of GHG flows for the “reorganizations” clusters with which it connects: cluster #7 for forestry reorganizations (*via* the TI “terrestrial carbon sequestration”); cluster #5 for bioenergies, *via* GHG emissions (“$CO_2$ concentration,” “methane emissions,” and “$N_2O$ emissions”); cluster #4 for “pasture” reorganizations *via* the TI “soil organic matter.” The cluster is also strongly linked to cluster #3, on climate change, with which it takes on the aspect of general biophysical context, in addition to its dimension as an impact.

Cluster #2, “Agricultural practices, LUC, and water resources (quantity and quality),” describes a series of impacts on water quality (TI “water quality,” “non-point pollution,” “eutrophication,” etc.), water quantity (TI “water balance,” “water resources,” “water use,” etc.), and on the effects of soil erosion, which impacts water quality (TI “erosion and soil degradation”) (see Table 2.3). This cluster is linked to varying degrees with various reorganizations (with the exception of the management of forest ecosystems): urbanization (cluster #8) *via* TI relating to quantitative water management and the TI “erosion and soil degradation”; bioenergy (cluster #5) *via* life cycle analyses; animal production *via* pasture systems (cluster #4) although in this case the link is weaker. Cluster #2 is also strongly linked to cluster #3, on climate change, presumably because climate change can affect precipitation regimes and alter climate zone suitability for different crops.

The most extensively studied reorganization of agricultural and forestry systems and/or spatial planning linked to land-use change are thus urbanization, the development of the bioenergy sector (appearing in the literature from the year 2000 on), changes in the management of forest ecosystems, and, to a lesser extent, grassland management.

The principal determinants that seem to give rise to these reorganizations are of two contrasting types: climate change, which can necessitate adjustments in agricultural practices or even call for a major rethinking of existing agricultural systems; and spatial planning policies, since these have the potential to allow, promote, reduce, or even forbid land-use change, notably among the different use categories of arable land/grasslands/forests/built-up areas.

The most studied environmental impacts within the corpus are primarily those relating to biodiversity, changes in atmospheric greenhouse gas concentrations, and water resources. Impacts on soils are examined less often, usually in connection with urbanization and grassland management.

Issues relating to food production seem to be strongly linked to bioenergy production (presumably *via* competition or the use of by-products).

This analysis of the overall map thus confirms the presence of several themes that have been widely studied and described in the literature, including the global context of climate change; reorganizations linked to urbanization and bioenergy production; and LUC impacts on GHG fluxes, carbon pools, and biodiversity.

The important position occupied by issues related to water resources is more difficult to interpret: it may be related to the context of climate change, generally hypothesized to lead to reduced water availability which may then necessitate changes in land use (in other words, water as a determining factor); or it may be related to land-use changes that result in increased water consumption, thus impacting water availability.

Certain themes are only weakly present, including those linked to LUC and livestock production and those related to LUC and food consumption. We can hypothesize that these are emerging topics and thus appear marginal within a map representing articles published over a long period.

### 2.3.3 Changes over Time in the Themes Addressed by the Corpus

To further identify changes and trends within the corpus, we extended our analysis using a feature of the CorTexT platform and the CorTexT Manager software that generates a dynamic representation of the corpus over time. Using the criterion of publication date, the software automatically divides the corpus into three parts of approximately equal numbers of items. The periods so determined are listed in the following table (Table 2.4).

This repartitioning of the articles by time period shows that during the first 30 years (1976–2007), fewer articles were published on our topic than during either the second or the third periods, each 4 years in length (2008–2011; 2012–2015). It would no doubt be interesting to create time periods like this using key dates with

**Table 2.4** Number of publications per time period

| Period | Number of publications |
|---|---|
| 1976–2007 | 1691 |
| 2008–2011 | 1906 |
| 2012–2015 | 2133 |

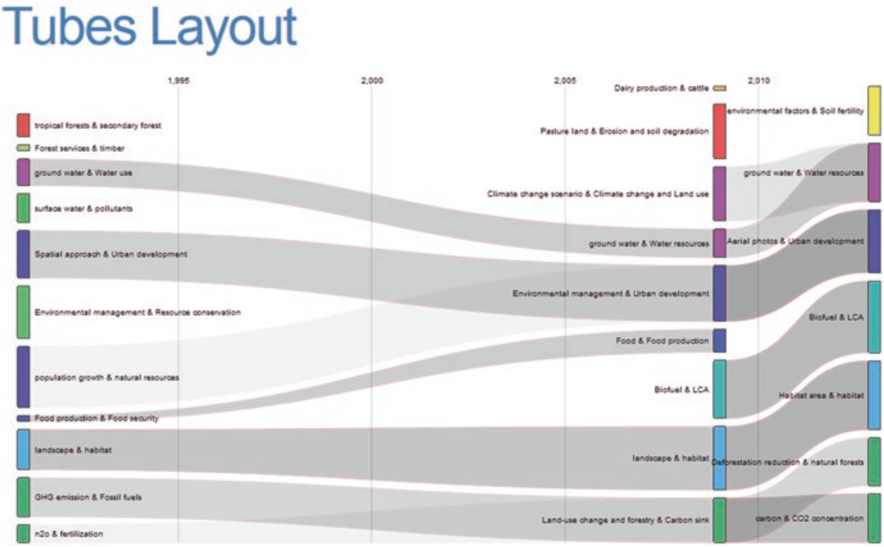


**Fig. 2.3** Schema showing changes in themes across the different time periods, in a "tubes" format

respect to the study context, such as major regulatory changes or the establishment of international research agendas. This is particularly true for the first period of 30 years, which could surely be subdivided into key contextual phases. It is less true for the two later periods, however (4 years being short relative to the pace of scientific publication), suggesting that there is little likelihood of revealing more meaningful trends by adjusting the cut-off dates.

Using this chronological division, CorTexT then creates maps to represent the three periods and schematizes the changes in the different clusters from one period to the next (see Fig. 2.3). This type of graphic uses a "tubes" format to link the clusters identified for each period. This format helps us observe the changes in different themes and their interactions over the established time periods.

Observing the structure of the clusters for the most recent time period (2012–2015), we find essentially the same structure as on the overall map: reading from bottom to top we find the identical clusters #6, #7, #1, #5, and #8; the cluster "ground water and water resources" is a merging of clusters #2 and #3 (distinct in the previous period); the cluster "environmental factors and soil fertility" is very similar to cluster #4 of the overall map. The width of the tubes is proportional to the number of publications present in the cluster. The dark tubes link those clusters (themes) that are strongly consistent from one period to the next, and which thus structure the dynamic of change for the field of the study.

This representation thus enables us to observe the increase or decrease in the number of publications for each theme, the separation or merging of different themes over the different time periods, the emergence of new topics and the fading of others from view.

#### 2.3.3.1 Summary Description of Clusters for the Three Time Periods

In the first period, eleven themes linked to land-use change were identified by CorTexT. These include themes related to reorganizations, such as “deforestation in tropical regions,” “forest ecosystem management,” “land use policy and agricultural practices,” “farm pasture systems and intensification,” “socioeconomic determinants and urbanization,” “food (production and security)”. Other themes relate to environmental impacts, including “water resources,” “impacts on soil and water,” “impacts on species biodiversity and landscape biodiversity,” “GHG emissions and carbon fluxes,” and “$N_2O$ and $CH_4$ emissions.” These themes do not all receive equal levels of attention, with some generating more publications than others (as expressed in the size of the different clusters).

In the second period there are fewer clusters than in the first period, with a total of nine themes appearing across the period. This reduction in the number of themes results from the merging of several clusters from the first period, with the cluster “management of forest ecosystems; carbon, $N_2O$ and $CH_4$ fluxes” appearing as a fusion of the three clusters “management of forest ecosystems”, “GHG emissions and carbon fluxes” and “$N_2O$ and $CH_4$ emissions”. These themes were studied separately during the first period and began to be considered together in scientific articles published in the more recent period.

In the third period, the clusters formed in the second period evolve further, with a merging of some clusters and a splitting of others. A description of these mergers and divisions is given below in the description of overall patterns of change.

#### 2.3.3.2 Hypotheses to Explain Changes over Time with Respect to the “GHG Emissions” Question

Up until 2007 (the first time period), emissions of $CH_4$ and $N_2O$ linked to LUC were considered separately from $CO_2$ emissions. This can be explained by the fact that before being studied as a GHG, $CO_2$ had long been studied as a phase in the carbon cycle and an essential component for photosynthesis, meriting focused research on questions of $CO_2$ fixation in biomass and in the soil, without necessarily being concerned with emissions budgets. It is only in the second time period that we see research develop to construct complete GHG emissions budgets, beginning in two contexts: first, for forest ecosystems, reflected in the merger of the two clusters “GHG emissions and carbon fluxes” and “$N_2O$ and $CH_4$ emissions” and the disappearance of the smaller clusters “management of forest ecosystems” and “tropical deforestation;” and second, for bioenergy production, reflected in the emergence of the cluster “GHG and bioenergy.” In the third period, the themes of forest management and greenhouse gas fluxes separate: here we can hypothesize that the theme “LUC and forests” addresses questions of deforestation and afforestation that are not limited to GHG budgeting and, in parallel, that full GHG budgets now constitute a theme that is no longer linked solely to forests, as is confirmed by the persistence of the cluster “bioenergy and GHG.” We are thus left in the third period with three clusters that are relatively close in their makeup to clusters #5, #6, and #7 on the overall map.

#### 2.3.3.3 Hypotheses to Explain Changes in the Handling of the Topic “LUC and Food”

This theme is continuously present, although minor, in the first and second periods, and then seems to disappear. In fact, we find it incorporated into the cluster emerging in the second period to address bioenergy and GHG: this could potentially be explained by the fact that the impact of LUC on food security is now preferentially considered from the perspective of competition for land between food and non-food crop production.

#### 2.3.3.4 Hypotheses to Explain Changes in the Handling of the Topic “Water and Climate Change”

Studies addressing the impacts of LUC on water are present in all three periods, with a strong increase in such studies in the third period, where the cluster “water resources” merges with the cluster “climate change,” appearing in the second period: We are thus left with a cluster jointly addressing the two themes. This dynamic helps us understand the overall map for the full corpus, where we saw two strongly linked clusters: cluster #2 (water resources) and cluster #3 (climate change). Viewed in terms of the temporal dynamic, these two clusters are fully distinct in the second period but merge in the third period, which the overall map can only render imperfectly. This strengthened link between climate change and the “water resources” topic can be explained by two complementary hypotheses: first, one of the determinants of climate change-induced LUC is a change in precipitation regimes, so we can imagine there are publications examining a link between water and climate change resulting in LUC. Second, the expansion of agricultural areas as a response to climate change is likely to impact water consumption, which some publications must address. Publications of the second type belong to the study theme because they measure an environmental impact; this is not necessarily the case with publications belonging to the first type.

#### 2.3.3.5 Hypotheses to Explain Changes in the Handling of the Topic "Biodiversity"

The impact of LUC on biodiversity is continually in evidence as a topic in all three periods. In more qualitative terms, in the most recent period we see studies appear examining ecosystem services (a concept brought to the fore by the Millennium Ecosystem Assessment (2005).

#### 2.3.3.6 Hypotheses to Explain Changes in the Handling of the Topic "Urbanization"

This topic is present in the first period and then expands in the more recent periods by incorporating the question of impacts on soils – a shift that seems to reflect a rise in concern over the loss of agricultural land. In the second period, this development may also be considered in connection with an adjacent cluster relating to agricultural practices, notably "intensification." This probably reflects the emergence of studies of land use at the regional level, particularly those employing the land sharing vs. land sparing concept, in which the degree of production intensification is a key factor.

#### 2.3.3.7 Hypotheses to Explain Changes in the Handling of the Topic "Pasture and Soils"

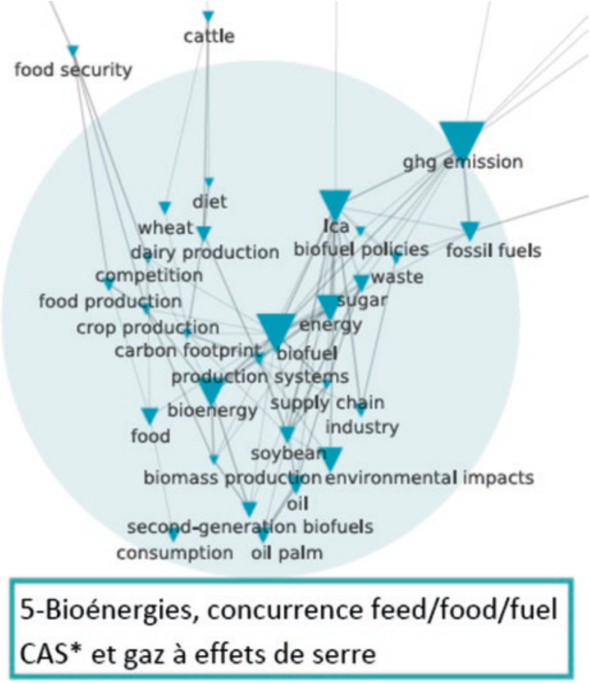
For these two themes, interpreting the temporal dynamic is challenging and does not yield clear information. Publications addressing impacts on soils seem to be related to two types of reorganizations: urbanization and changes in of grazing intensity. The connection to land-use change is unclear in the latter case, however.

## 2.4 Detailed Study of the "Non-food Biomass" Theme

Analysis of the theme of non-food biomass production was pursued in more detail in order to characterize the range of this area of study. We were particularly interested in the different types of bioenergy examined, types of LUC considered, and types of impacts studied beyond the dominant approach of assessing the effects of bioenergy production on GHG emissions. We were also curious to see how research on second-generation biofuels is developing. First-generation biofuels are increasingly controversial, and this fact is reflected in public policy. The EU is planning to exclude first-generation biofuels from its energy transition plan, for example.

The sub-corpus used to construct this cluster (Réchauchère et al., Chap. 1, this volume) was made up of 1785 references (see Fig. 2.4). The thematic identifiers "biofuel," "GHG emissions," and "LCA" form the cluster's centers of gravity.

**Fig. 2.4** "Bioenergies" cluster from the overall map. Detail from Fig. 2.2 (5730 references): 1976–2015



These references were extracted to create the sub-corpus on "Bioenergy." This enabled us to conduct a more detailed analysis of the development of this theme over time and its links to other themes within the corpus.

Co-occurrence maps were created using the same parameters as for the overall map (the top 150 thematic identifiers from the index present within the sub-group).

The following map (Fig. 2.5) shows the resulting detailed analysis of the bioenergy cluster.

The same textual analysis procedure as that performed for the full corpus was then applied to all the articles belonging to the bioenergy cluster from the overall map (see Fig. 2.2). All 1785 articles were published between 1990 and 2015. Four topical centers or poles were identified for this time frame (see Fig. 2.5).

- The first pole consists of a cluster centered on bioenergy reorganizations, linked on one side to a cluster joining questions of "land use policy" and "food security" to questions of water resources management, and on the other side to a cluster describing impacts on biodiversity and methods used to study those impacts. We can hypothesize that this formation corresponds to two trends within the study of bioenergy: (1) competition between bioenergy crops other land uses, especially food production; and (2) the principal impacts of bioenergy production, on biodiversity and on water resources.

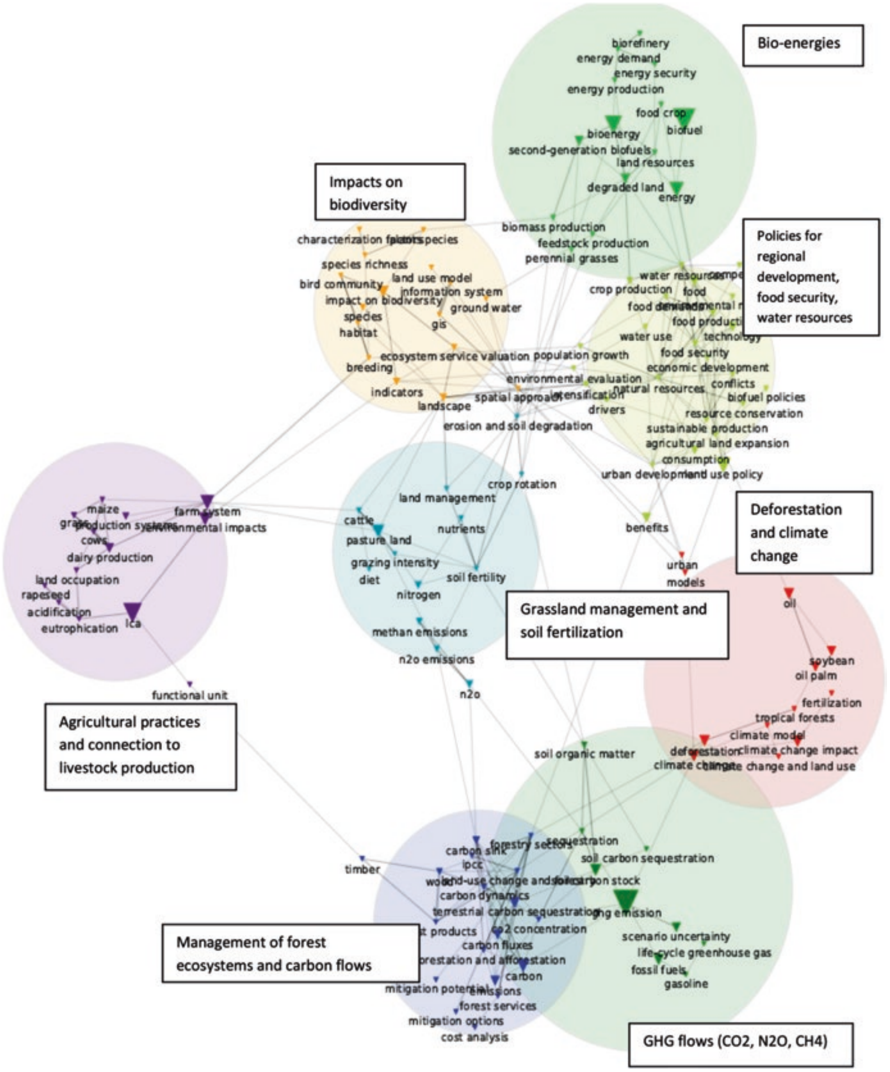


**Fig. 2.5** Map of the sub-corpus on bioenergy for the full time period

Compared with its corresponding item on the overall map, the "bioenergy" cluster here is made up of a group of thematic identifiers more tightly focused on issues specific to energy and bioenergy, with two relatively common thematic identifiers, "bioenergy" and "biofuel," and with second-generation biofuels also present. Restricting the corpus to the topic of non-food biomass thus makes a group of TIs visible that are critical to a proper understanding of the topic. These TIs are strongly linked to another TI in the cluster, "degraded land," which is in turn linked to the "land-use policy" cluster *via* TIs related to food security. This may reflect the fact that solutions are being sought to avoid competition between the production of energy biomass and food production (for instance by using degraded land areas for the biofuel production, especially second-generation biofuels, said to be more tolerant of less fertile soils).

- A pole centered on reorganizations toward livestock production.

This pole is made up of a single cluster centered on "farming systems," with a link to dairy production among other topics. It is connected to grassland management via "cattle," "pasture land," and "farm system." It is also connected to the cluster on biodiversity impacts. Also important within this pole are the closely linked thematic identifiers "LCA" and "environmental impact," emphasizing the privileged position of LCA within environmental impact studies. It is more difficult to explain the position of these two TIs here, adjacent to questions of livestock production, rather than adjacent to bioenergy.

- A pole on carbon fluxes, with three, strongly interconnected clusters addressing GHG fluxes, and thus primarily oriented toward impacts.

This pole is structured around a large cluster at its center focused on GHG emissions and on carbon sequestration in soils. It is connected to a cluster on deforestation in tropical areas, referencing among other things the production of soybeans and palm oil. Finally, it is connected to a third cluster addressing specific aspects of carbon sequestration in forests as a climate-change mitigation strategy.

- A pole at the center of the map, on grassland management and $CH_4$ and $N_2O$ emissions.

This pole addressing grassland management and soil management. It occupies a central position and is connected to three other poles:

– The thematic identifiers "methane emissions" and "$N_2O$ emissions" link it to the pole on greenhouse gas fluxes.
– The thematic identifiers "cattle" and "pasture" are connected to the pole on livestock.
– The thematic identifiers "soil fertility" and "erosion and soil degradation" form links with the poles on bioenergy and on biodiversity impacts.

These thematic identifiers thus explain the central position of the grassland management cluster. Grassland management is topically linked to questions of environmental impacts resulting from grassland conversion into arable production; the use of grasslands for livestock production; and the relative benefits of grasslands vs. forests in terms of carbon storage in soils. Interestingly, the links between the grassland management cluster and the clusters on bioenergy, biodiversity impacts, and food security are all made *via* the TI "erosion and soil degradation." Two possible interpretations suggest themselves: either these represent studies documenting the negative environmental impacts of plowing up grasslands for bioenergy production, or they may correspond to articles describing the production of bioenergy crops on degraded and low-productivity grasslands, thus avoiding direct competition with food production. The question could be clarified by closer examination of these specific articles.

## 2.5 Conclusion

A textual analysis performed using CorTexT enabled us to systematically review the themes addressed in 5730 academic articles (from 1976 to 2015) identified by a bibliographic search request combining keywords related to environmental assessment with keywords related to land-use change. The articles address different types of spatial reorganizations leading to LUC and the resulting environmental impacts.

The corpus was created by searching for scientific articles at the intersection of the two fields of environmental assessment (broadly defined) and land-use change. By examining the intersection of these two fields, we hoped to identify publications addressing all types of reorganizations of agricultural and forestry systems and spatial planning leading to land-use change; information on the biophysical and socioeconomic determinants underlying these reorganizations; and the range of environmental impacts resulting from these land-use changes. The maps obtained from the textual analysis were interpreted from the perspective of the causal sequence "reorganizations/land-use changes/environmental impacts." Based on relationships of co-occurrence, we sought to identify to what extent and in what forms this causal sequence was examined in the corpus, including, where relevant, the biophysical and socioeconomic determinants underlying the observed reorganizations.

The **overall map** of co-occurrences within the corpus enabled us to identify the principal themes addressed in the selected articles, assigning each theme to the appropriate step in the causal sequence (socioeconomic and bio-physical context ➔ reorganizations of agricultural and forestry systems, or spatial planning ➔ changes in land use ➔ environmental impacts). The map revealed eight clusters:

- one cluster addressing climate change as an aspect of the biophysical context, strongly linked to a cluster examining carbon fluxes in terrestrial ecosystems and greenhouse gas fluxes in general;
- one cluster showing a close association between a reorganization (bioenergy production) and an environmental impact (greenhouse gas emissions);
- three "reorganizations" clusters relating to urbanization, grassland management, and forestry management;
- two "impact" clusters relating to impacts on biodiversity and impacts on water resources, respectively.

This breakdown according to the dominant aspect of each cluster is a simplification – within each cluster and among the links to other clusters we find keywords that help resituate these dominant themes within the overall causal sequence. It can nevertheless provide us with an initial understanding of the corpus contents.

**A dynamic representation of the development of the corpus** over time offers additional information and suggests other avenues for investigation:

- trends in the study of GHG: studies looking at all GHG from agricultural sources ($CO_2$, $N_2O$, $CH_4$) have become more common; articles increasingly focus on a specific type of reorganization (forestry ecosystems, bioenergy production);

- we can hypothesize a rise in concerns about potential land competition between food, feed, and bioenergy production (from 2008 on);
- the emerging climate-change issue is strongly linked in recent years to the question of impacts on water resources (since 2008);
- certain themes have remained steady over time, such as LUC impacts on biodiversity and the effects of urbanization on LUC.

**A more detailed analysis** of land-use change related to the production of "non-food biomass":

This reorganization is situated within a socioeconomic context of regional development policies tied to both national and supranational (EU) regulations, with proximate references to the issue of land degradation. With land-use policies having become increasingly sensitive to questions of land competition, references to land degradation may be interpreted as reflecting the emergence of studies on the use of degraded lands for bioenergy production (notably second-generation biofuels) as a way of reducing land competition with food crops. Our detailed analysis of the sub-corpus on "reorganizations toward non-food biomass production" also highlighted the importance of life-cycle analyses as a methodology for studying the impacts of bioenergy production. We thus have at our disposal a substantial number of studies sharing a common methodology that could be the focus of further analysis. It would likewise be interesting to examine whether different methodologies have a statistically significant influence on the findings of environmental assessments.

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# Chapter 3
# The Environmental Impacts of Non-food Biomass Production Through Land-Use Changes: Scope, Foci and Methodology of Current Research

**Benoît Gabrielle, Aude Barbottin, and Julie Wohlfahrt**

**Abstract** Biomass production has developed significantly in the latest decades to meet the growing needs of the bioeconomy sector, a trend which is expected to continue in the near future to substitute dwindling fossil resources. Concerns were recently raised on the consequences of expanding feedstock production on land-use worldwide, prompting a surge in scientific publications. These consequences may be analysed through a three-step causal chain relating drivers of feedstock production, changes in land-use (LUC), and environmental impacts such as greenhouse gas (GHG) emissions, biodiversity, water resources, soil quality, or atmospheric pollution. Here, we set out to examine how this booming area of research is currently structured in terms of foci, methodologies employed, or types of LUC studied. It appeared especially relevant since this research bears a degree of performativity in that it is likely to influence and shape policies in the realm of the emerging bioeconomy sector.

A qualitative analysis of the body of 236 articles selected through a systematic literature survey evidenced the following characteristics. There was a strong emphasis on 1G biofuels, and on lignocellulosic feedstocks in relation to 2G biofuels. Most of the LUC reported occurred in Europe and North America, and the region involved by indirect LUC was rarely specified. In terms of methods to work out the causal

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chain, the use of simple, ad'hoc calculations or statistics dominated except for impact assessment, where LCA was relied on very frequently. The use of economic modeling to predict LUC in response to various drivers was far from dominant, but tended to result in more conservative outcomes regarding the environmental benefits of bio-based products, in comparison with fossil-based value-chains.

Most studies focused on single products, feedstocks, or environmental impacts, and the connection with food/feed production was rarely addressed per se. The analysis of multi-functional systems, integrating non-food and food production and value-chains should be fostered, along with interactions between the various research communities currently seeking to address the LUC-mediated impacts of the bio-based economy.

**Keywords** Biofuels · Bioenergy · Biomass · Land-use change · Direct · Indirect · Impact assessment · Drivers.

## 3.1 Introduction

Biomass production for non-food applications (in particular modern forms of bioenergy) has developed significantly in the latest decades in response to tensions on the fossil energy market and rising oil prices, and this trend is expected to continue in the near future to substitute dwindling fossil resources (Chum et al. 2011). Concerns were recently raised around the consequences on land-use via land-use changes (LUC) incurred when expanding feedstock production (e.g., Searchinger et al. 2008), and prompted a surge in scientific publications on this topic over the past 10 years (see Réchauchère et al. – General Introduction, this volume). Attributing LUC to biomass production and ultimately the rising demand for end-products (e.g., biofuels) requires the elicitation of mechanisms relating feedstock production to changes in land-use or land management, and their impacts on the environment. These relationships may be analysed as a three-step causal chain: drivers of feedstock production, LUC occurring in response to this demand, and environmental impacts, given that the bioeconomy could generate co-benefits (Chum et al. (2011). Impact categories included greenhouse gas (GHG) emissions, biodiversity, water resources, soil quality, or atmospheric pollution. Note that these impacts may be negative or positive. Socio-economic impacts of bioenergy expansion (e.g. on food prices) were not included per se in the analysis as they were out of scope of the overarching project behind this study (see Introduction of special issue).

Although reviews of this emerging and dynamic research area were recently published (e.g., Broch et al. 2013; Berndes et al. 2013), none of them involved a systematic survey of literature encompassing the full causal chain between biomass expansion drivers and environmental impacts. A review of such approaches, referred to as "meta-studies", concurred in highlighting this gap in the context of "land-use science" (van Vliet et al. 2016), and revealed a decoupling between drivers of LUC and their environmental impacts. This trend emerges as a structural feature of this research area, and others may be suspected given the emphasis on some value-chains in response to aggressive policy targets – the push for biofuels in the transport sector providing a prime example (Liska and Perrin 2009). It is interesting to note in the systematic survey on LUC literature reported in this volume (Réchauchère et al., Chap. 1, this volume) that only the body of articles pertaining to non-food biomass production was deemed large enough to allow for a quantitative analysis (El Akkari et al., Chap. 2, this volume). Other drivers emerged such as urban development and sprawl (Seto and Kaufmann 2003), increase in demand for wood (Lambin et al. 2001), food and feedstuff (Tilman et al. 2002; Defries et al. 2010; Bajželj et al. 2014), and agricultural intensification (Brunelle et al. 2015). Altogether, these topics appeared either too recent to provide the necessary evidence or not fully addressed in terms of a drivers to impacts chain.

From a phenomenological perspective, scientific literature informs us on the current state of the technological and natural systems which are observed and assessed by researchers, but it is also performative to some extent since it can influence the state of these systems by emphasizing specific topics (Callon 2008). Thus, it appears of great interest to describe the current trends in this literature to point at recent evolutions in the aspects of biomass production studied and its impacts, and the type of systems which are particularly scrutinized.

Here, we set out to examine how the body of work on the relationships between LUC, bio-based products and their impacts on ecosystems is currently structured in terms of foci (vis-à-vis bio-based chains, feedstocks, or world regions), methodologies employed, or types of LUC studied. The objective was to assess current scientific practices and to reveal trends emerging across this large body of references regarding the various steps of the causal chains addressed. This overview also aimed at highlighting possible gaps and biases with current research, and potential improvement routes.

## 3.2 Materials and Methods

### *3.2.1 Literature Survey and Identification of a Relevant Subset of References*

In a first step, we surveyed the scientific literature on LUC and environmental impacts in general between 1975 and February 2015, and retrieved a body of 5730 articles from two databases relevant to these topics (Web of Science and CAB; see Réchauchère et al., Chap. 1, this volume for more details). All references included keywords related to land-use changes, but another constraint was that references should cover the three steps of the drivers to environmental impacts causal chain. A last constraint consisted of mentioning at least one bio-based end-product, one type of biomass feedstock, and one category of environmental impacts among the following: global warming, consumption of non-renewable resources, biodiversity, water resources, soil quality, atmospheric pollution, human health, and ecotoxicity. Thus, references addressing LUC in relation to food or fuel production but not dealing with the environmental consequences were excluded from the analysis. Note that the impacts of non-food biomass production could be either positive or negative.

An automated textual analysis of the papers' abstracts, titles and keywords evidenced a series of themes structuring this set of references (El Akkari et al., Chap. 2, this volume), and the subset on the impacts of biomass/bioenergy through LUC effects was selected. It was further screened manually by a dozen of experts in the fields covered by this literature (economics, ecology, agronomy, forestry, sustainability assessment), and winnowed down to 241 references. Those were further analysed in details in terms of scope, LUC types, methodologies employed, and overall outcomes. The review articles were excluded,[1] so that the following results pertain to an overall body of 236 articles.

### *3.2.2 Factors Driving Biomass Production: A Typology of Feedstock Types and End–Uses*

As we are dealing with LUC-mediated environmental impacts induced by biomass production, it seems important to classify biomass feedstocks with respect to their end-use to compare them on this basis (i.e. for a similar end-product). On the other hand, biomass production systems are highly diverse, ranging from corn to produce ethanol to forestry. It is safe to assume the magnitude of LUC and environmental impacts is also highly dependent on feedstock types (Mosnier et al. 2013), and it is also relevant to differentiate them. Since one biomass feedstock type can be used for several end-uses, and one bio-based product can be obtained from different feedstocks (Table 3.1), we defined two distinct typologies regarding biomass feedstocks and end-uses, respectively.

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[1] Cherubini F., N.D. Bird, A. Cowie, G. Jungmeier, B. Schlamadinger, S. Woess-Gallasch. (2009) Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. Resour. Conserv. Recycl. 53,(8), 434–447. DOI: https://doi.org/10.1016/j.resconrec.2009.03.013.

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**Table 3.1** Feedstock groups and potential non-food end-uses (non-food uses of biomass feedstocks presented in this table are based on expertise regarding current purposes of the biomass feedstocks)

| Feedstock groups | | Dedicated to non-food production | End-uses | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1G biofuels | 2G biofuels | Heat | Electricity | Biogas | Material |
| Mono end-use 1G biofuels | Barley<br>*Hordeum vulgare* | No | X | | | | | |
| | Camelina<br>*Camelina sativa* | No | X | | | | | |
| | Cassava<br>*Manihot esculenta* | No | X | | | | | |
| | Jatropha<br>*Jatropha curcas* | No | X | | | | | |
| | Rapeseed<br>*Brassica napus* | No | X | | | | | |
| | Soybean<br>*Glycine max* | No | X | | | | | |
| | Sugar beet<br>*Beta vulgaris* | No | X | | | | | |
| | Other 1G biofuel feedstocks | No | X | | | | | |
| Multi end-uses flex-crops | Corn<br>*Zea mays* | No | X | | | | X | X |
| | Oil palm<br>*Elaeis guineensis* | No | X | X | X | X | X | |
| | Sugar cane<br>*Saccharum officinarum* | No | X | X | X | X | X | |
| | Sorghum<br>*Sorghum bicolor* | Yes/No[a] | X | X | | | X | |

(continued)

**Table 3.1** (continued)

| Feedstock groups | | Dedicated to non-food production | End-uses | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 1G biofuels | 2G biofuels | Heat | Electricity | Biogas | Material |
| Multi end-uses lignocellulosic | Agricultural residues | Yes | | X | X | X | X | X |
| | Eucalyptus<br>*Eucalyptus globulus* | Yes | | X | X | X | | X |
| | Forest residues | Yes | | X | X | X | | X |
| | Herbaceous | Yes | | X | X | X | X | X |
| | Miscanthus<br>*Miscanthus x giganteus* | Yes | | X | X | X | X | X |
| | Poplar<br>*Populus* | Yes | | X | X | X | | X |
| | Switchgrass<br>*Panicum virgatum* | Yes | | X | X | X | X | X |
| | Wheat<br>*Triticum aestivum/durum* | No | X | | | | | |
| | Willow<br>*Salix* | Yes | | X | X | X | | X |
| | Wood | Yes | | X | X | X | | X |
| | Short rotation coppice (SRC) | Yes | | X | X | X | | X |
| | Other broadleaf trees | Yes | | X | X | X | | X |
| | Other resinous trees | Yes | | X | X | X | | X |
| | Other 2G biofuel feedstocks | Yes | | X | X | X | | X |
| Other | Livestock residues | Yes | | | | | X | |
| | Other feedstocks | Yes/No[a] | | | | | | |

[a] Within these feedstock groups, some species or varieties are dedicated to non-food production while other are flex-crops

Regarding feedstock types, only 185 articles out of 236 specified the biomass species studied or provided enough information to retrieve them. Some feedstocks occurred frequently and were set aside, while others were grouped in order to assess their representation in the body of references. For instance, we separated articles dealing with miscanthus or switchgrass but combined those about ryegrass, undefined cellulosic feedstocks or alfalfa under the generic class "herbaceous", as these feedstocks were seldom mentioned in the articles. We regrouped the different feedstocks in 28 classes, listed in Table 3.1. Biomass feedstock types can be characterized regarding their specificity toward non-food production (dedicated vs flex-crop species, e.g.: oil palm can be considered as a flex-crop as it products either for food or non-food feedstocks) and/or among non-food productions (e.g.: sugar beet is used for first generation biofuel production whereas miscanthus can be used for second generation biofuels, heat or electricity production). We distinguished flex-crops and feedstocks dedicated to non-food production, and also single or multi-purpose non-food feedstocks (Table 3.1).

As far as end-uses of biomass was concerned, the articles were reviewed by experts with a background on the various steps of the drivers to impact chains, who reported one or several end-uses for the feedstocks under scope. Even if most feedstocks can be used for a range of purposes, we based our analysis on those reported by the authors of the articles in order to highlight the overall orientations of current literature. For two articles, the authors did not state the end-use of the biomass. Thus, the database we analysed regarding this comprises 183 articles.

### *3.2.3 Types of Land-Use Changes Analysed*

The set of 236 articles was analysed according to the type of land-use changes (LUC) simulated ex-ante or observed ex-post, and the associated environmental impacts. Out of this set, 38 did not specify the LUC type or analysed only indirect LUC, and 4 articles actually analysed changes in management practices in the absence of LUC, or changes in the use of biomass. Thus, we were able to specify direct land-use changes for only 194 articles.

In order to analyse LUC, six types of land-uses were defined: (1) Arable land, i.e. land dedicated to crop production for food, feed or biofuel purposes; (2) Perennial Biomass Crops (PBC), corresponding to an area dedicated to biomass crops other than forest and annual crops; (3) Grassland, corresponding to harvested or grazed pasture for animal farming, natural grassland…; (4) Forest area (natural or managed for wood production including wood fuel); (5) Artificial areas such as urban area, industrial wasteland; and (6) Wetlands.

LUC was described as the change from one land-use type to another, considering each time the initial and the final land-use. 30 land-use changes could occur, i.e. Arable to Perennial Biomass Crop or Grass to Arable…6 'Shifts' were also considered related to crop management, purposes or end-uses. These shifts, i.e. Arable to Arable when crop initially used for food or feed were converted as biomass crop in biofuel, are not associated with direct LUC.

**Table 3.2** Broad categories of methods used in the various steps of the chains, sub-categories and examples taken from the set of references reviewed

| Broad category | Sub-categories included | Example |
|---|---|---|
| Economic model | General or partial equilibrium model, micro-economic model, farm model | Mosnier et al. (2013) |
| Process-based model | Biophysical model, ecosystem model, land-surface model, ecological models, hydrological model | Hoque et al. (2014) |
| Life-cycle assessment | Life-cycle impact assessment, consequential LCA | Silalertruksa and Gheewala (2012) |
| Basic calculations | Linear relationships, simple ratios | Rasmussen et al. (2012) |
| Statistical analysis | Uncertainty and sensitivity analysis, regression, meta-analysis, use of statistical data | Fialho and Zinn (2014) |
| Other | Multi-criteria-analysis | Villamor et al. (2014) |

### 3.2.4 *Methods to Assess LUC and Their Impacts*

In terms of methodology, the textual analysis on the original body of references pointed to a broad array of methods used to work out the drivers to impacts chain (see El Akkari et al., Chap. 2, this volume). These were grouped into a dozen of main categories relative to their nature (simple calculations, statistical analysis or process-based models), or referring to more elaborate frameworks such as LCA. These broad categories are listed in Table 3.2, along with a reference exemplifying the use of these methods in relation to LUC. Readers are referred to these articles for a detailed presentation of these methods, or to recent papers reviewing the methods currently used to estimate LUC and assess their impacts (Berndes et al. 2013; Ben Aoun et al. 2013). Note that the categories in Table 3.2 are not exclusive since for instance many consequential LCA studies also rely on economic models to estimate LUC associated with the value-chain analysed.

### 3.2.5 *Land-Use Change Drivers: A Strong Emphasis on Biofuels and an Apparent Disconnect with Food Systems*

Figure 3.1 shows the distribution of biomass crops species or group of species among the studied articles. Among those, 111 dealt with a single feedstock, 33 with two of them and 41 with at least 3. A majority of articles (37% of the overall set) deal with the most common first-generation (1G) bioethanol species: either corn, sugar cane and/or wheat. Regarding 1G biodiesel, the most studied species are soybeans, oil palm and rapeseed (25, 22 and 28 articles respectively). Even though 1G biofuel feedstocks predominated overall, the single most studied biomass crop was miscanthus (30 articles), followed by switchgrass (24 articles). Second-generation (2G) biofuel feedstocks (miscanthus, switchgrass and herbaceous species in general) were studied in 69 articles, which highlight the emphasis of research on these

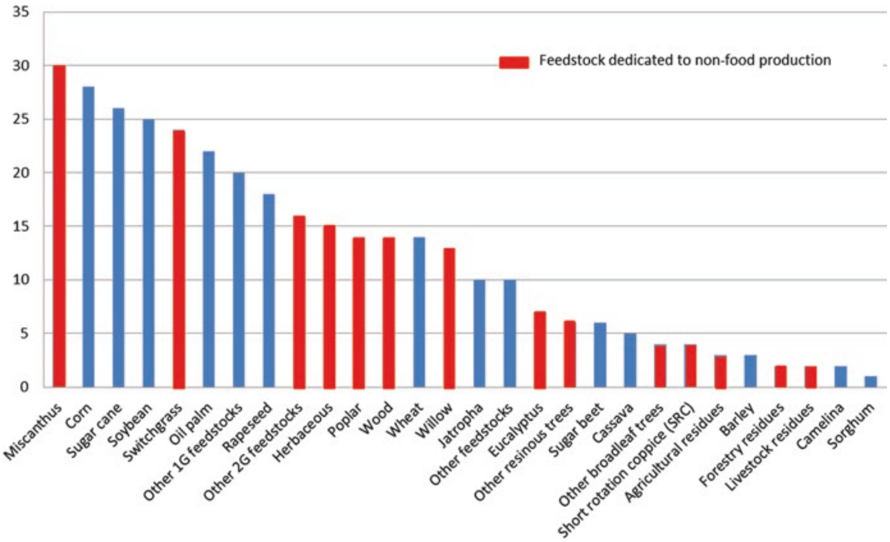

**Fig. 3.1** Distribution of articles among different feedstocks and feedstock groups

new feedstocks and processes. One hundred and fifty-five articles (84% of the total set of references) dealt with at least one dedicated biomass feedstock, and 179 (97% of the articles) with at least one flex-crop. Twenty-seven articles (36% of the articles dealing with more than 1 feedstock, 15% of the corpus) dealt with at least one dedicated and one flex-crop. Overall, these two kinds of biomass feedstocks are evenly represented in the articles, but there are few studies actually comparing them.

Regarding end-uses, most articles dealt with 1G biofuels (38% of articles; Fig. 3.2), while 52% of them dealt with other energy uses (2G biofuels, combustion or biogas), and 10% dealt with non-energy end-uses such as biomaterials or chemicals. Biogas was considered as an end-use in only 5% of the articles reviewed, and agricultural, forestry or livestock residues were only mentioned in 7 articles. Except in some intensive systems involving whole-plant digestion (Meyer-Aurich et al. 2012; Yeh and Sperling 2010), biogas production was considered as a mean to valorize residues, such as animal manure, straws or any by-product coming from agricultural or agri-food processes (see e.g.: Tidaker et al. 2014; Hamelin et al. 2014). The small representation of biogas end-use and residues feedstocks in the set of references may be related to the fact that their impacts on land-use changes is seen as limited and thus not considered an important scientific topic.

Regarding the multiplicity of end-uses, 108 articles dealt with a single biomass end-use, 49 with two and 26 with more than two end-uses (Table 3.3). Articles dealing with a least two end-uses are of two kinds (Table 3.4): 56 compared different species for several end-uses (e.g.: 33 articles compared the impact of first and second biofuel production), while 19 compared the potential of one feedstock to produce several kinds of energy sources (e.g., bioethanol and heat production with sugar cane – Garcia et al. 2011). Only a few papers mentioned the connections between their bio-based systems and food production systems.

**Fig. 3.2** Biomass end-uses distribution among the articles of the database

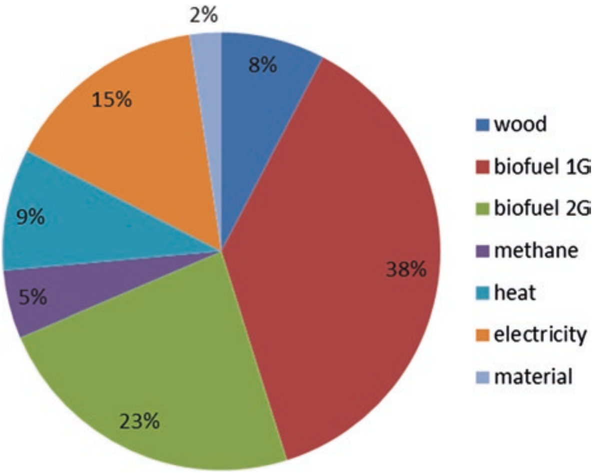

**Table 3.3** Breakdown of articles according to the number of end-uses addressed (one, two or more)

| | 1G Biofuels | 2G Biofuels | Wood | Heat | Electricity | Biogas | Material | Number of articles |
|---|---|---|---|---|---|---|---|---|
| Single end-use | 66 | 19 | 12 | 2 | 4 | 2 | 3 | 108 |
| 2 end-uses | 35 | 33 | 3 | 7 | 18 | 1 | 1 | 49 |
| More than 2 end-uses | 11 | 18 | 8 | 18 | 23 | 12 | 3 | 26 |
| Total | 112 | 70 | 23 | 27 | 45 | 15 | 7 | 183 |

**Table 3.4** Co-occurrence of end-uses in articles dealing with multiple end-uses (75 articles).

| | Biofuel 1G | Biofuel 2G | Wood | Heat | Electricity | Biogas | Material |
|---|---|---|---|---|---|---|---|
| Biofuel 1G | | 33 | 5 | 6 | 15 | 5 | 1 |
| Biofuel 2G | | | 6 | 13 | 20 | 8 | 2 |
| Wood | | | | 5 | 6 | 4 | 0 |
| Heat | | | | | 23 | 8 | 2 |
| Electricity | | | | | | 11 | 4 |
| Biogas | | | | | | | 1 |
| Material | | | | | | | |

## *3.2.6 A Wide Range of Land-Use Changes Analysed but a Paucity of Underlying Data*

### 3.2.6.1 Number and Types of LUC Analysed in the References

From 1 to 36 LUC types were simultaneously considered in the articles analysed. Most of them concentrated on one or two land-use types and on the environmental impacts resulting from LUC (this applied to 70 and 64 articles out of the total of 194 considered here, respectively). These articles dealt with: shifts in the end-use of production or management, i.e. biomass production or biofuel (see for example Gonzalez–Hernandez et al. 2009), the use of crop or forest coproducts for energy production (e.g., Hamelin et al. 2014), shift in crop management (e.g., Bright et al. 2012) or the development of a new crop and his impact on biodiversity (Brandt and Glemnitz 2014). When LUC occurred, they were oriented toward crop production (40 articles), perennial biomass crop production (72 articles with 10 articles on wood production), wetlands restauration (1 article) or changes from arable crops to PBC or wood (3 articles).

Thirty-one articles considered more than two LUC simultaneously, generally orientated toward perennial biomass crops or crops for biofuel production. The development perennial biomass crops or crops for biofuel production mainly occurs instead of grass or wastelands (13 references), natural areas (3 references), forest or cropland (5 articles). When different LUC scenarios were compared simultaneously, they were generally developed in regards of public policies or foresight studies. These scenarios associate LUC and shift in the end-use of products or management. Most of the LUC analysed dealt with the transition from arable land or grassland to perennial biomass crops (respectively 16 et 14% of the LUC analysed), or that from grassland or forest to arable land for food, feed or biofuel production (respectively 14% and 11% of the LUC analysed; Fig. 3.3).

The main type of indirect LUC analyzed involved changes from forest to arable crops (35 occurrences), PBC (16 occurrences), or grassland (15 occurrences); the replacement of grassland by PBC came second (17 occurrences), followed by the replacement of arable crops by perennial biomass crops (13 occurrences), forest (11 occurrences) or grassland (eight occurrences; Fig. 3.4). According to the scenarios, shifts in the end-use of productions are described as a consequence of LUC (17 occurrences).

In 11 out of 236 articles, only indirect LUC are specified, i.e. without a direct LUC being explicitly described. These indirect LUC concerned shifts to arable crops (e.g., Newell and Vos 2011; Kloverpris and Mueller 2013; Nguyen and Hermansen 2012), forest or perennial energy crops (Slade et al. 2009) or changes from natural areas in response to shifts in the end-use of biomass production in another geographical region (Villoria and Hertel 2011). This lack of precision is also due to the frontier between indirect and direct LUC being often unclear in the scientific literature. The former frequently includes the latter even if this may remain implicit.

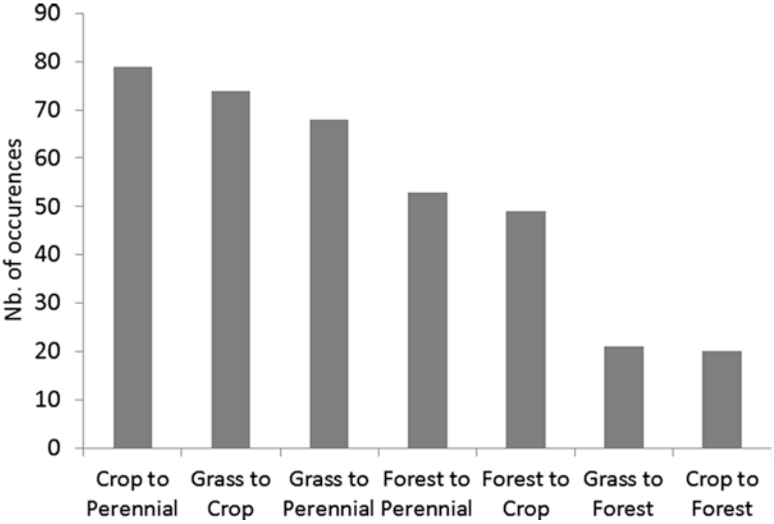

**Fig. 3.3** Occurrences of the seven main types of LUC identified in the body of articles analyzed. Only LUC that occurred in more than 3% of the articles are presented here. These seven classes make up 74% of all LUC types characterized. Occurrences correspond to the number of times a given LUC is mentioned in the 236 articles. *Perennial* perennial biomass crops

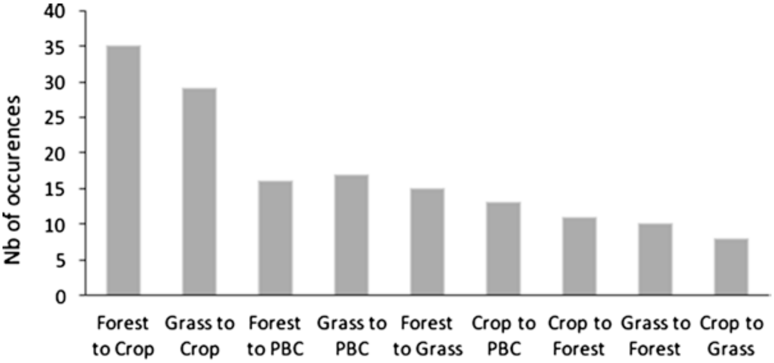

**Fig. 3.4** Occurrences of the 9 main types of indirect LUC identified in the articles analysed. Only LUC that occurs in 3 or more articles are presented here. They represent 83% of the indirect LUC types characterises. *PBC* Perennial Biomass Crop

#### 3.2.6.2 Nature of the Data Used to Represent LUC and Dynamic Trends

Different types of land-use data were used in the articles reviewed. A minor fraction of studies did not report the source of their data, while a majority combined different sources of data (98 articles out of 194 mobilized two or more sources of data). These sources included public statistics (47 articles), land-use or soil databases (respectively 57 and 4 articles), land-use surveys (35 articles) or experts' interviews (39 articles). Lastly, literature data on LUC was used in a large fraction of the articles (124 out of a total of 194).

Ninety-three articles focused on historical trends or prospective scenarios of LUC. The interval between the occurrence of the LUC and the evaluation of its impact varied from one year to a hundred years. 77 articles developed ex-ante scenarios and 22 article deal with ex-post scenarios only. Here again, the time interval between LUC and environmental impact evaluation was highly variable (respectively 1–2000 years and 1–45 years). Forty-nine percent of the study considered a time horizon less of equal to 2020; 12% of the study considered a time horizon of respectively 2025 and 2030; 9% a time horizon of 2040 and 18% a time horizon of 2050 or higher (half of these studies considered a time horizon higher than 2080).

### *3.2.7 An Absence of Methodological Consensus Favoring Simple, ad'hoc Calculations*

Figure 3.5 reports the occurrence of the various categories of methods used to work out the drivers to impacts causal chain, for its three steps and overall. In principle, some methods were more appropriate for a particular step: for example, economic models are more suitable to relate drivers to land-use changes than to assess the environmental impacts of these changes. However, they were also mentioned in this step because some of these models integrate impacts, such as GHG emissions. The distinction between the first two steps (drivers and LUC) was also far from clear-cut, and both curves follow a similar pattern as a result (see top two graphs of Fig. 3.5).

Overall, the dominant categories were 'basic calculations' and 'no methods', with a compounded occurrence of about 45%. Since review papers were set aside, this implies that about one study in 5 relied on literature data in the estimation of at least one of the steps of the causal chain. A similar proportion used very simple relationships. For example, indirect LUC would be addressed by substituting 1 ha of food crop diverted to bioenergy with an 'equivalent' area of natural ecosystem needed to produce a similar amount of foodstuff (Turconi et al. 2014). This was especially true for the first step of the chain, involving the drivers of LUC, since the latter were considered exogenous to the studies. The starting point was typically a scenario analysis of future developments of bioenergy, prescribing an extra demand for non-food biomass. More sophisticated methods involved economic models, looking at broader policy frameworks (e.g., related to climate change mitigation),

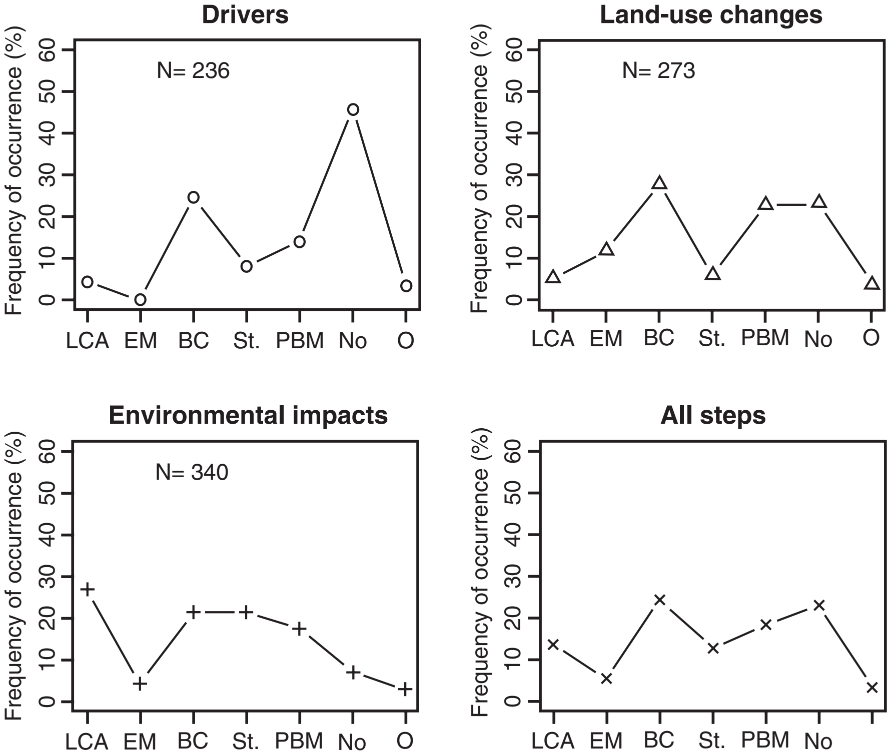

**Fig. 3.5** Breakdown of methods reported in the body of 236 articles for the three steps of the drivers to impacts causal chain, and overall (when compounding the 3 steps). Key to labels: *LCA* life-cycle assessment, *EM* economic models, *BC* basic calculation, *St.* statistical analysis, *PBM* process-based model, *No* no method, *O* other

process-based models, or LCA. The latter corresponds to the consequential approach (Ekvall and Weidema 2004), which seeks to take on board the implications of decisions regarding the development of a particular end-product, including LUC, and has been extensively applied to biomass in the last decade. This explains why LCA is present in the second step of the chain, relative to the evaluation of land-use changes, but its occurrence is rather marginal. Other than the simple methods (or absence thereof), this second stage was dominated by process-based models, followed by economic models but with a twice lower occurrence. This is counter-inutitive since the latter could be expected to predominate. However, the difference between both models may not be so significant because economic models may be counted by some experts as process-based models. Also, they were often used in combination (11 occurrences out of the 35 cases involving economic models), e.g. to determine the production function of different types of land-use and target the most profitable conversions in response to changes in market prices (e.g., Mosnier et al. 2013).

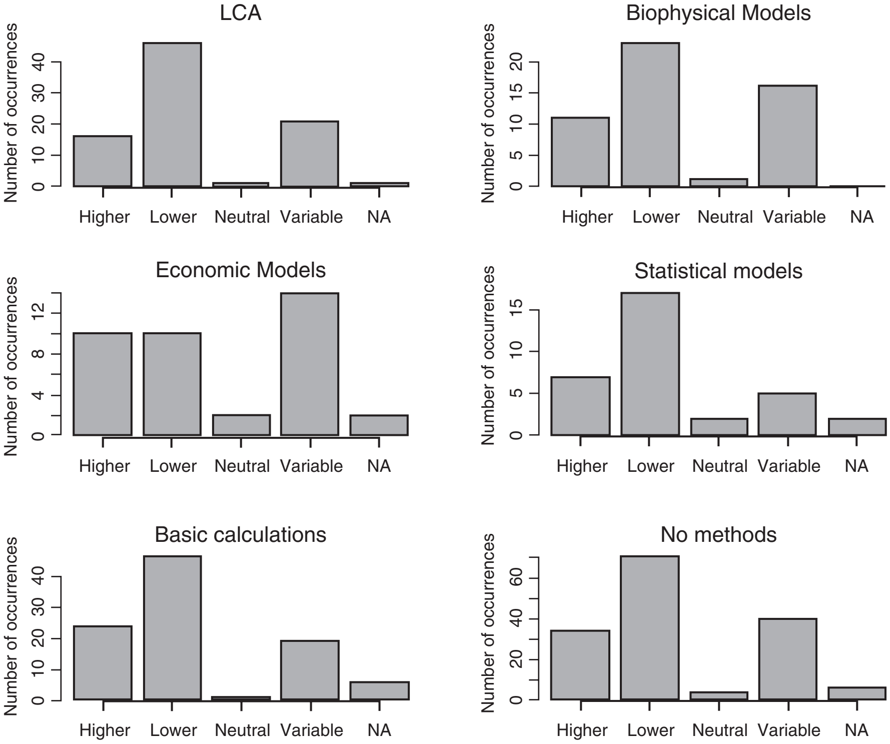

**Fig. 3.6** Outcomes of the comparison between bio-based scenarios and their counterfactuals, according to the methods used in any of the three steps of the drivers to impacts chain. *NA* not reported

As could be expected, LCA or its variant life-cycle impact assessment (LCIA) dominated the last step of the chain regarding the environmental impacts of LUC, with a 25% share of the methods reported (Fig. 3.5). Simpler methods still dominated overall (with a compounded share of 40%), while process-based models accounted for nearly a fifth of the studies. The 'no method' category was at its lowest (10%), as was that pertaining to 'other methods', implying that authors generally put a larger emphasis on impact assessment when addressing the LUC causal chain compared to its first 2 steps.

The possible link between the type of methodology employed and the outcome of the comparison between bio-based products and a counterfactual scenario, involving a fossil-based product most of the time, was tested for the GHG emissions. The latter represented the first impact investigated overall, being the focus of about 80% of the articles reviewed (Bamière et Bellassen, Chap. 6, this volume). The outcome of the comparison, as reported by the experts who read the articles was either positive (producing biomass leading to higher GHG emissions), negative (lower emissions), neutral, variable, or unclear. The patterns of this outcome was similar across the main types of methods (Fig. 3.6), but some differences emerged:

the use of LCA more often lead to lower emissions, and with less variable results than the other methods, while economic models stood out by an even balance between higher and lower emissions, altogether with more variable results.

### *3.2.8 Time Trends in LUC-Related Research*

Since LUC-related research is very recent in the context of non-food biomass production, it is interesting to look at time trends in terms of research foci. Very few articles were published prior to 2007 (Fig. 3.7), and the year that followed was clearly a turning point after which the indirect LUC effects of 1G biofuels came under scrutiny (see Searchinger et al. 2008), prompting a stark increase in the output of publications on this topic. The main focus of these references was liquid biofuels and biomass production from energy crops in general – the latter having superseded the former as of 2011 (Fig. 3.7). Articles dealing with biomass production from forests or conversion to this land-use were marginal in the body of articles analysed (Fig. 3.8), while perennial crops received an increasing focus and the shift to arable crops levelled off.

In terms of methodologies, most categories followed the trend of rising occurrences after 2008, indicating that no specific framework was established (Fig. 3.9). This also implies that despite a growing availability of such methods to address LUC, most authors chose not to implement them and go along with simple methods (grouped as ‘basic calculations’), which remained popular throughout. However, they were closely trailed by two categories which rose sharply after 2008: LCA and process-based models. The use of economic models also grew rapidly from only a few occurrences in 2009 to about 10 in 2014, still half as frequent as the two previous categories.

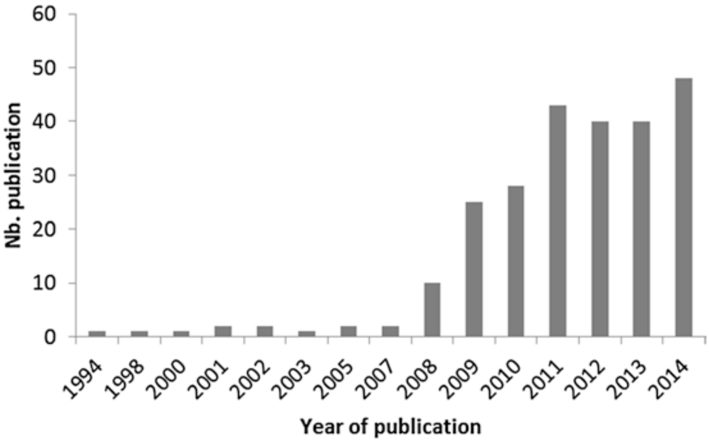

**Fig. 3.7** Number of articles analyzed according to their publication year

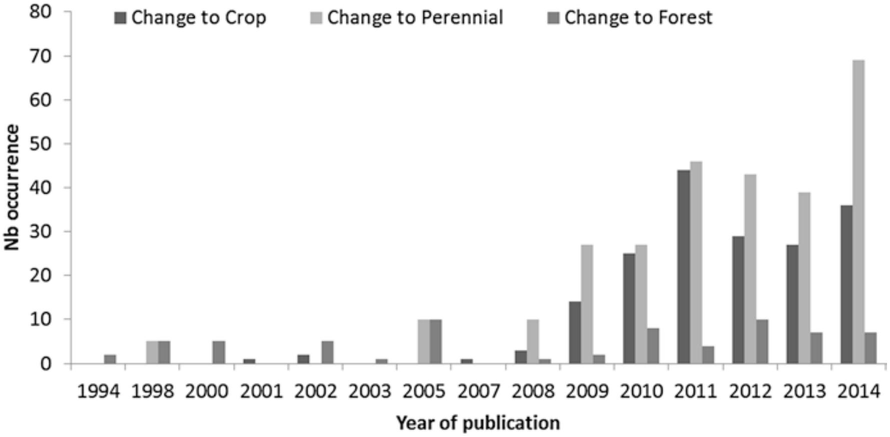

**Fig. 3.8** Land Use Changes identified according to the article year of publication. Three type of changes were defined: a shift to cropland (Change to crop), to perennial crops (Change to perennial) and to forest (Change to Forest). A given publication may deal with one or more of these LUC types

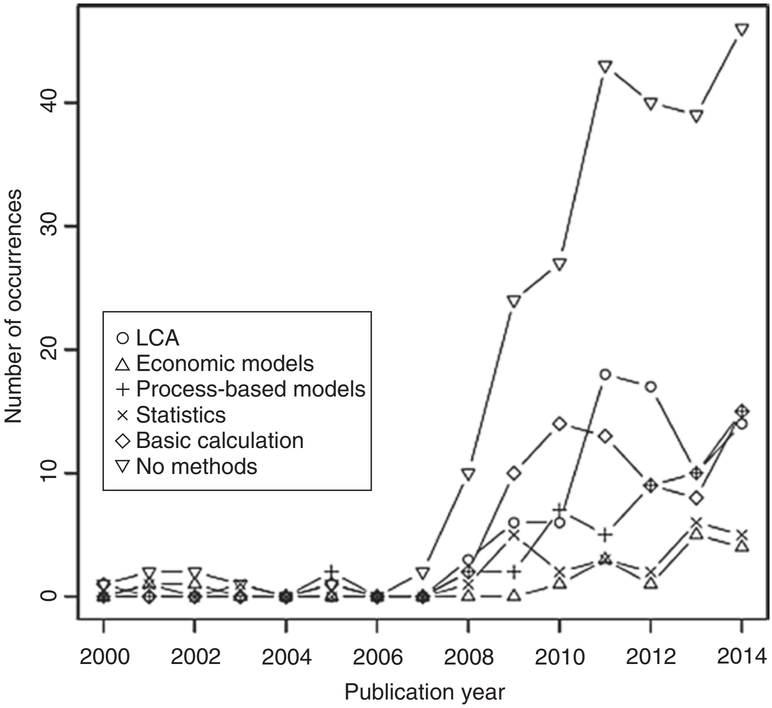

**Fig. 3.9** Annual occurrences of the methods used in the reviewed literature between 2000 and 2014

**Table 3.5** Localization of Land Use Changes according to world regions

| Localization of Land-Use Changes | Number of occurrences |
|---|---|
| Africa | 10 |
| North America | 70 |
| South America | 44 |
| Asia | 30 |
| Europe | 74 |
| World | 21 |
| No information | 19 |

## *3.2.9 Geographical Scope*

### 3.2.9.1 Areas Affected by LUCs

North America and Europe together accounted for the majority of the LUC studied (respectively 74 and 70 articles; Table 3.5). Africa represents a small part of the studies (10 articles overall, e.g.: Laurijssen and Faaij 2009; Romijn 2011). About 18% of the articles did not specify any particular location of the LUC or involved very large scales (19 and 21 articles, respectively; Table 3.5). 94% of the articles of the papers investigating LUC in North America were focused on the United States, with only 3 publications reporting on Canada. Articles considering Europe dealt with seventeen different countries: Germany (9 articles), Denmark (5 articles), United Kingdom (9 articles) and Ireland (7 articles) featured prominently in this subset.

Whatever the geographical region concerned, the main land-use changes considered involve changes from arable land, grassland or wood land to perennial energy crop production (from 30% to 50% of the LUC described in the articles). The second larger subset involve the shift from woodlands or grasslands to arable crops (from 14% to 50% of the LUC described). The majority of LUC toward forest or woodland takes place in the European region (23% of the LUC for this geographic region). We can also notice that LUC studied for the South-American region involved changes from natural areas or wetlands to arable or perennial crops.

Indirect land-use changes were less precisely described in the articles. When reported they were factored into the assessment of their impacts (see for example Acquaye et al. (2012) or Kauffman and Hayes (2013)). Only 36 articles out of 194 specified indirect LUC in their scenarios, of which 25 simultaneously considered direct and indirect LUC. In 18 articles, indirect and direct LUC occurred in the same geographical region or country. When indirect LUC took place in another geographical region than direct LUC, the latter mainly occurred in South-America, or elsewhere in the world but without the specification of a given region (Table 3.6). Possible interactions between the location of LUC and the methods used to evaluate their effects were investigated by comparing the two major world regions analyzed overall: Europe and the US. The distribution of methods were similar, with a few exceptions: biophysical models were used more frequently in the US studies to estimate LUC per se, whereas LCA was more heavily used in the Europe-based studies in lieu of biophysical models for impact assessment (not shown).

**Table 3.6** Localization of indirect Land Use Changes as a function of direct LUC according to world regions

| Localization of direct Land-Use Changes | Localization of indirect Land-Use Changes | Number of occurrences |
|---|---|---|
| North America | Elsewhere in the Word | 5 |
| | South America | 1 |
| | Asia | 1 |
| | North America | 1 |
| South America | South America | 8 |
| Asia | Asia | 4 |
| Africa | Africa | 2 |
| Europe | Elsewhere in the Word | 5 |
| | South America | 5 |
| | North America | 2 |
| | Asia | 2 |
| | Europe | 3 |
| **World or no information specified** | Somewhere in the world without information or no information specified | 11 |

### *3.2.10 Current Research Foci and Trends*

The above analysis points to several qualitative trends in terms of current research on non-food biomass production and LUC-mediated environmental impacts. First, there is a sharp focus on biofuels for transport, compared to other end-uses, which does not reflect the current structure of bioenergy use worldwide, where heat and power dominate in terms of energy produced, even when looking at modern value-chains (Chum et al. 2011). Although increasing heat or power production from biomass is not neutral in terms of LUC (Fritsche et al. 2010), there is clearly a higher political emphasis on biofuels combined with a rapid growth compared to other usages of biomass, which prompted the emergence of a highly productive research area (see Fig. 3.7). Notable policy drivers for biofuels include the Brazil ethanol program or the European Union energy Directive (EC/2003) which set a 5.75% target for biofuel incorporation in transportation fuels within 2010. The dramatic increase in 1G biofuel production that ensued raised important sustainability issues (e.g., Farrell et al. 2006), leading to a wealth of studies designed to refine the analysis of their environmental impacts. On the other hand, the importance of 2G biofuels in the articles surveyed shows that even though this value-chain is not commercial yet, prospective research on its potential impacts are important.

Secondly, most publications focus on a single end-product (e.g., biofuel or bioplastic), and consider only one impact category. Multi-functional uses of biomass are present via the co-products generated by the conversion process (as animal feed, power, or heat, typically), but rarely following the cascading approach of biomass use that is often advocated to improve the economic and environmental performance of bio-based products (Ragauskas et al. 2006).

In terms of methodology, process-based models and simple models (sometimes referred to as ‘causal descriptive chains’) predominated. Economic models were less frequently-used than expected, but provide an alternative to the simple approaches. Both types of methods are not easy to compare or reconcile, especially since they evolved from distinct scientific communities (agricultural economics versus industrial ecology). However, their respective limitations are well known (Ben Aoun et al. 2013), and more interactions between these options would be desirable to overcome them. The selection of a method is not neutral in terms of outcome, since for example LCA appeared less conservative in terms of GHG emissions from LUC than others, especially the economic models (EM). Most LCA used the attributional framework under which the studied system does not expand to include indirect effects, while it does with EM. A recent meta-analysis on the iLUC of 1G biofuels concluded similarly that simpler methods lead to lower estimations of GHG emissions from iLUC compared to economic models (De Cara et al. 2012).

Lastly, the outcomes of the studies strongly rely on the assumptions for direct LUC – for instance whether biomass plants are established on marginal land, cropland or permanent grassland.

## 3.3 Research Gaps and Avenues for Future Work

In terms of methodology, there clearly appears a need to improve our insight into the drivers and mechanisms leading to LUC when attempting to characterize the environmental impacts of non-food biomass development. Indirect changes in particular were poorly reported in the studies retained for this analysis, even though it should be acknowledged that this does not hold for the literature on LUC in general (e.g., Lotze-Campen et al. (2014), which is much larger (the Van Vliet et al. 2016 review reported a total of 11,429 primary studies on LUC). In particular the main driver of LUC, changes in the prices of agricultural commodities was not included in our literature search equation. Thus, the following section and conclusions only apply to the body of work addressing the environmental impacts of biomass that factor in land-use changes, as captured by our survey. Simple methods, or absence thereof predominate, meaning a lot of estimates are rather speculative. More sophisticated approaches such as economic modeling or consequential LCA are increasingly resorted to, but appear difficult to reconcile, having evolved from two different lines of research and purposes. Consequential LCA seeks to address the environmental impacts of bioenergy, following the LCA framework (Berndes et al. 2013), while the economic modeling is interested to examine the effects of bioenergy development on GHG emissions and climate in general at global scale (e.g., Mosnier et al. 2013). These two approaches are sometimes combined in the consequential LCA approach, as was the case in 20% of the LCA studies surveyed here, but they are still mostly used separately. Regarding the evaluation of LUC-mediated environmental impacts, the fact that no articles referred to the ecosystem services (ES) framework, which is widely used in the literature related to land-use (van Vliet et al.

2016) is interesting. LCA or economic models are both ill-suited to tackle local impacts such as biodiversity, water resources or ecotoxicity, which the ES framework is better equipped to deal with (Haines-Young and Potschin 2010). As a result, these impacts were only addressed in a minority of articles within the body surveyed here (see Gaba, Chap. 8 and Bispo, Chap. 5, this volume). This appears as a major gap in current research on biomass and LUC. Again this reflects a segregation between different scientific communities, this time both in terms of impacts and methodologies employed. Scale is another issue between these approaches since LCA tended to focus on regional to national scales whereas economic modeling mostly involved continental to global scales. Top-down approaches at these scales is essential to capture all the effects of developing non-food biomass, but make it hard to grasp opportunities at the local organization levels (e.g., at farm and catchment scales) arising from the spatial variability of soil properties or marginality factors (Berndes et al. 2013).

Very few articles dealt with multiple feedstocks or end-uses in the context of LUC effects. Although biorefinery approaches implementing such strategies have led to a growing number of publications lately (a simple search on the Web of Science data base reveals that the number of publications dealing with biorefineries increased from only 72 in 2007 to 687 publications in 2015), they have not been appraised as a way to reduce LUC-mediated impacts. One reason may be that these strategies usually emphasize non-energy end-products, such as platform chemicals or biomaterials, which are seen as niche markets generating little pressure on land-use. However it would be worthwhile to reverse the focus and examine how biorefineries can reduce the land footprint of bioenergy products through multiple uses (Dale et al. 2010).

The lack of mention of food systems in the articles reviewed here reveals a close but somewhat different matter: it highlights the disconnect between research communities traditionally focused either on energy or food security, which also reflects sectoral policy frameworks. There are few incentives to seek synergies between the two systems, except the obvious relationships through co-products. Strategies such as multi-functional land-use (e.g., agro-forestry systems), integrated logistics and/or co-processing of biomass for feed, food or fuel purposes (Eranki and Dale 2011; Kline et al. 2017) or closed-loop systems (e.g., Collet et al. 2014) deserve more attention, as opposed to the simple, mono-functional product systems which represent the core of the articles analyzed here.

## 3.4 Conclusion

Over the past decade there has been a surge in the number of articles seeking to elucidate the causal chains between the drivers of non-food biomass production, their effects on land-use worldwide, and the associated environmental impacts. A qualitative analysis of the body of 236 articles pertaining to this booming area of research evidenced the following salient features: a sharp focus on 1G biofuels, and on lignocellulosic feedstocks for prospective value-chains, mostly 2G biofuels; LUC occurring overall mostly in Europe and North America, where the demand for bio-based products was located, with indirect effects rarely specified and concentrated in South America; the use of simple, ad'hoc methods to work out the causal chain except for impact assessment, where LCA predominated; an use of economic modeling of LUC in response to drivers on the rise, but far from dominant; a tendency for these models to produce more conservative outcomes regarding the benefits of bio-based products on GHG emissions compared to other methods, especially LCA.

A majority of the articles reviewed focused on a single end-product, biomass feedstock, or environmental impact, and the connection with food/feed production was rarely addressed per se although it was implicit when deriving LUC estimates. It appears relevant to encourage the analysis of multi-functional systems, integrating non-food and food production and value-chains (*e.g.*, Guo et al. 2016), and also to foster interactions between the various methodologies and research communities currently getting to grips with the LUC-mediated environmental impacts of the bio-based economy.

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# Chapter 4

# Review of the Impacts on Soils of Land-Use Changes Induced by Non-food Biomass Production

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**Abstract** Over the past decade, the exponential growth in the production of biomass for energy use has raised concerns as to the environmental impacts of this type of land use, as well as the potential land-use changes (LUC) associated with an extension of agricultural land areas. Determining the environmental impacts of an expanding bioenergy sector requires reconstructing the chains of cause and effect from the determinants of land-use change (both direct and indirect) and land-use practices through to the impacts of those practices. Conducting an exhaustive literature review from 1975 to 2014, we identified 241 articles relevant to this causal chain, thus enabling an analysis of the environmental impacts of LUC for bioenergy. This chapter presents the results of a detailed literature analysis and literature review of the 52 articles within this corpus specifically addressing impacts on soils. The variation in soil organic carbon (SOC) is the most commonly used impact indicator, followed by soil loss to erosion and, to a lesser extent, the potential for environmental acidification as determined by life-cycle assessments. Background and transitional SOC levels during LUC affect the predictive value of estimated final SOC variations but are not generally accounted for in default static stock-difference approaches. Perennial crops tend to be better at maintaining or even improving SOC levels, but results vary according to pedoclimatic and agronomic conditions. The mechanisms involved notably include protection of the soil surface with a dense perennial cover and the limitation of tillage operations, especially deep plowing; accumulation of organic matter and SOC linked to biomass production, especially belowground production of rhizomes and deep, dense root systems; associated reductions in nutrient loss *via* runoff and erosion. Nevertheless, additional research is needed to improve our understanding of and ability to model the full range of processes underlying soil quality and LUC impacts on soil quality.

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## 4.1 Introduction

The production of biomass for bioenergy and biomaterials has expanded considerably in recent years. This expansion is likely to continue given a context in which substitutes must be found for diminishing fossil resources (Chum et al. 2011). Increases in biomass production present challenges linked to the expansion of agricultural land area and the potential impacts of land-use change (LUC) (Searchinger et al. 2008). These concerns have prompted a sharp increase in the number of scientific publications on this topic over the past 10 years . Assessing the environmental impacts of bioenergy development requires reconstructing the chains of cause and effect from the direct and indirect determinants of land-use change and land-use practices through to their various impacts, all along the value chain from biomass production to the final product.

Recent studies have surveyed these issues and documented emerging research trends (e.g., Broch et al. 2013), but no published work to date has conducted a systematic literature review corresponding to the three steps of this causal sequence: from the determinants of increased land use for bioenergy, through changes in land allocation, up to the environmental impacts of biomass production; i.e., the "reorganization-LUC-impact" causal sequence. Indeed, a recent review of methodologies for analysis and meta-analysis of this causal sequence identified a disconnect between research examining the drivers of LUC, on the one hand, and work on environmental impacts, on the other hand (van Vliet et al. 2016). Environmental impacts can be diverse in nature, affecting soils, air quality, biodiversity, etc., but these various types of impacts are rarely considered together in the studies reviewed in the present chapter.

The aim of the overarching study, whose outputs are detailed throughout this volume, was to provide quantitative data, based on an exhaustive literature review, for the analysis of these causal sequences. The results are broken down into a meta-analysis accompanied by focused literature reviews of each stage in the causal chain: from the analysis of LUC drivers, to analyses of LUC, to assessments of the various categories of identified impacts. In the first step of the literature review, 5730 articles (from 1975 to 2014) relating to LUC in general were extracted from the Web of Science and CAB databases. The second step consisted of an automated textual search procedure (see El Akkari et al., Chap. 2 in this volume) to identify articles allowing for an analysis of the causal sequence reorganization-LUC-impact, including at least one impact category from the following list: climate change (greenhouse gas emissions), depletion of fossil/non-renewable resources or water resources, impacts on biodiversity or soil quality, atmospheric pollution, human health and ecotoxicity. This reduced the corpus to 1785 articles, which were then examined in more detail by a dozen scientific experts, seeking to identify articles addressing the full causal sequence as well as those featuring datasets available for the meta-analysis. This third step reduced the corpus to 241 articles. The present chapter describes the results of the focused literature review of the studies examining impacts on soil quality.

In the following section, a qualitative analysis of the causal sequences in this focused corpus enables us to appreciate the representativeness of these results in terms of geographic coverage, sectors examined, and the robustness of the methodologies and data employed. The subsequent section engages in a more detailed analysis of methodologies, impacts, and the mechanisms underlying those impacts.

## 4.2 Bibliometric Analysis

The corpus analyzed in this chapter consists of 52 of the 241 articles identified. Three-quarters of these articles were published in the last 4 years of the study period (i.e., 2011–2014) (Fig. 4.1).

### *4.2.1 Areas of Historical Importance More Strongly Represented Than Emerging Areas*

The majority of the land-use changes (LUC) examined in the corpus are located in the United States (30%) or Brazil (14%) (Fig. 4.2). At the continental level, the Americas account for 54% of locations and Europe for 30%, far ahead of Africa (5%), Asia (5%), and Oceania (2%). The remaining 4% correspond to two studies focused on the global level. The predominance of research focusing on the United

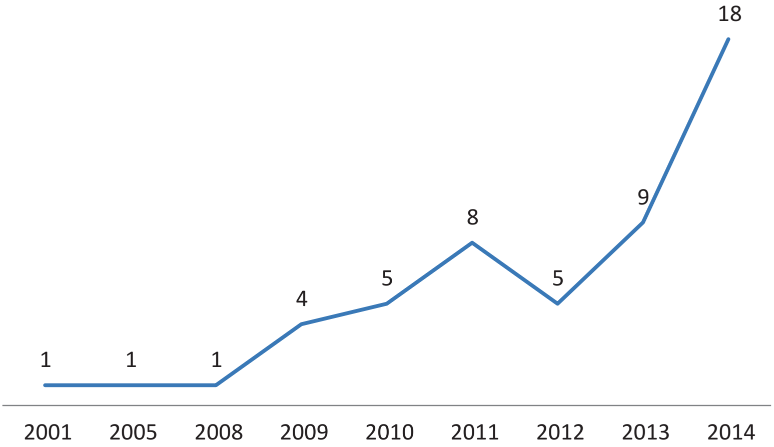


**Fig. 4.1** Number of publications on impacts of land-use change on soils by year (2001–2014)

Fig. 4.2 Case study locations

States and Brazil is likely due to a greater accumulation of research efforts given the longer history of the biofuel sectors in these countries. More recent developments in the European countries are notable at the aggregated continental level.

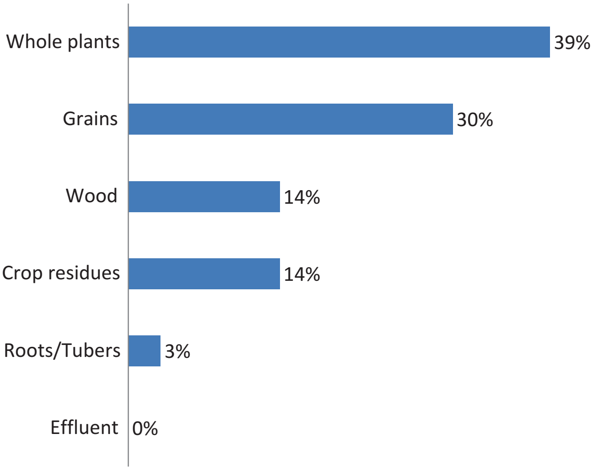
The information recorded during the experts' examination of the full corpus did not allow for the identification of all production areas, since some research articles consider multiple origins for plant products but not all of these origins were necessarily listed in the reading grid, notably in the case of imports of bioenergy feedstocks (e.g., palm oil from Malaysia is used in one scenario, but this country is not listed in the "location" field). We thus find only a few studies addressing emerging tropical regions for bioenergy production where land-use change for agricultural development is taking place most rapidly, such as in Indonesia, Malaysia, or Congo.

The scale of the research described in the articles is generally large. Approximately 60% of those studies for which the scale of spatial analysis was recorded were conducted at a level equal to or greater than a region or county. Similarly, where this information was recorded, land area considered for biomass provision exceeded 1000 ha in 70% of the articles, and exceeded 1,000,000 ha and 25% of the articles.

### 4.2.2 Crops Dedicated for Biofuels Predominate

The principal types of biomass represented are whole plants (all aboveground biomass harvested) or grains (Fig. 4.3). These trends appear robust despite the fact that biomass type was not systematically recorded (for 17% of the articles, the experts' review did not indicate biomass type). Double counting may also skew this breakdown (e.g., "Entire plant + wood," recorded for plantings of species used for short-term coppice rotations).

**Fig. 4.3** Breakdown of the subcorpus by biomass type (not noted in 17% of studies)



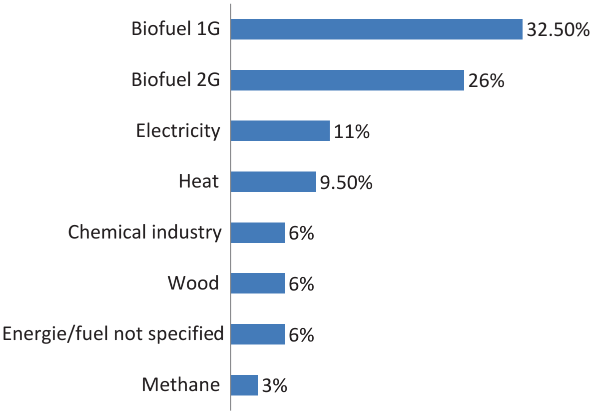


**Fig. 4.4** Breakdown of the subcorpus by final product type (not noted in 15% of studies)

An analysis of species distribution by biomass type could not be completed, since the list of species recorded was not exhaustive, notably as a result of the global studies reviewing numerous species without a fine level of detail. Nevertheless, the results suggest a prevalence of miscanthus, switchgrass and sugar cane (whole plants); soybean, rape, and maize (grains); poplar (wood); wheat (crop residue); and sugarbeet (roots/tubers). The principal final products examined were first- and second-generation biofuels (Fig. 4.4).

Agricultural practices for these biomass types were not systematically recorded in the studies, and so could not be analyzed: there were only 17 entries out of a total of 238 scenarios. Most studies focus primarily on LUC scenarios rather than on changes in agricultural practices scenarios that are unrelated to LUC in the strict sense of a change in land allocation. LUC are not necessarily associated with a change in practices defined as "crop diversification". Changes in "crop diversification" practices may be understood as a diversification at the level of the farm system rather than at the level of the land allocation mosaic. The "short-term coppice rotation" practice represented 40% of the 17 practice types recorded, which is understandable given the clearer correlation between this practice and an LUC type, i.e., the establishment of dedicated plantings as part of a new agricultural system.

### *4.2.3 Poorly Characterized Aspects of Land-Use Changes*

No clear trends appear in the corpus analyzed here as to the regulatory context of LUC (regulated = 33%, not regulated = 19%, not recorded = 48%), or as to the LUC timeframe (retrospective = 14%, prospective = 44%, both = 40%, does not apply = 2%). Years or time periods assessed with respect to LUC were also poorly recorded (in 62% and 77% of articles, respectively, these details were not provided).

In correlation with the major biomass types recorded (Fig. 4.3), the most important types of direct LUC involve conversions of forests, annual crops, or grasslands into perennial energy crops, which are mostly harvested as whole plants or grains (34%). Next in importance are direct LUC in which forests or grasslands were converted into annual crops (16%). Approximately 18% of the LUC examined relate, *a priori,* to a change in agricultural practices rather than to an LUC in the strict sense. Indirect LUC were examined 4 times less often than direct LUC, but trends are similar in terms of the types of land use involved.

### 4.2.4 Overview of Methods and Data Used

A survey of the methods used in the articles shows that efforts to model final impacts on soils are overall more common than characterizations of earlier stages in the causal sequence, i.e., modeling of the causes and types of LUC (Table 4.1). Specifically, the reorganization of land-use types is mostly either not recorded or is estimated according to basic calculations based on observations or suppositions of direct changes without a global modeling. Economic models, although widely used in the modeling of agricultural reorganizations and LUC, are not strongly present here. The most frequently used method for analyzing soil impacts is life-cycle

**Table 4.1** Overview of methodologies and data types utilized

| ***Steps in the impact chain*** | | ***Reorganization*** | ***LUC*** | ***Soil impact*** |
|---|---|---|---|---|
| **Method** | Not stated/other | **43/2%** | 17/3% | 4/12% |
| | Basic calculation | 23% | **33%** | 20% |
| | Statistical model | 5% | 7% | 7% |
| | Life Cycle Analysis | 8% | 9% | **31%** |
| | Biophysical/process-based/ecological model | 5/3/2% | 11/7% | 10/10/1% |
| | Economic model | 7% | 9% | 4% |
| | Meta-analysis | 2% | 1% | 1% |
| | Qualitative | - | 1% | 1% |
| **Type of data** | Not stated/other | 25% | 12% | 4/2% |
| | Scientific reference | 24% | 29% | **37%** |
| | Statistics/land use | 9/11% | 12/19% | 12/9% |
| | Field data (observations/measurements/interviews/expert opinion/climate/satellite imagery/soil data) | 8/6/1/13/1/1% | 5/5/-/12/4/-/2% | **10/10/1/11/4/-/- %** |
| | Global economic models | 1/- % | - | -/1% |
| **Accessibility of results** | Not stated/no information | **38/- %** | 25/1% | 5/- % |
| | Tables/figures/maps | **32/21/4%** | **33/25/4%** | **44/43/3%** |
| | Raw data/text | 1% | 7/3% | 2/2% |
| **Precision of results** | Not stated/no information/other | **58/35%** | **44/44%** | **20/35/11%** |
| | Standard error/standard deviation/confidence interval | 2/2/- % | 2/2/4% | 4/2/11% |
| | Sensitivity analysis | 4% | 4% | 18% |

NB: Totals ≠ 100% due to rounding

Cell shading corresponds to percentage totals: Light blue: >15–30%; Gray: >30–45%; Dark gray: >45%

*LUC* Land use change

assessment (LCA), followed by basic calculations relying notably on changes in quantities of biomass or carbon, followed by more mechanistic models.

Data types are better recorded for all stages of the "reorganization-LUC-impact" causal sequence. Literature references and statistical data are the most frequently found data types, particularly for land use. Nevertheless, data gathered in the field – including experimental data, climate data, and survey data – account for almost a third of the data used. Again, the final link in the causal chain, that is, the modeling of impacts, attracts most of the work of characterization, with the largest number of both literature and field data.

Finally, the results overall are not highly detailed. Data are mainly accessible in the form of tables, which do not include all stages of the causal chain; or in figures or maps presenting results in a more or less aggregated form. The statistical robustness of the results is not always noted, nor is the validity domain of the results always discussed.

## 4.3 Analysis of Soil Impacts

### *4.3.1 Few Impacts Addressed*

Soils are a complex resource, supporting many functions (Doran and Parkin 1994; Karlen et al. 2003; Patzel et al. 2000). These functions are enabled and may be affected by a variety of interacting physicochemical and biological soil properties and conditions. Impacts on soil quality, i.e., the capacity of a soil to support diverse functions, are as potentially numerous as all the possible combinations of modifications that may occur for these diverse soil properties. While some processes are broadly understood (e.g., erosion, acidification), the impact mechanisms connecting environmental conditions and agricultural practices to variations in soil properties, and their consequences for soil functions, have only been partially described (Karlen et al. 2003; Kibblewhite et al. 2008).

In the corpus considered here, only a few types of impacts on soils are described in detail. The impacts most often addressed are the levels of soil organic matter (SOM) and soil organic carbon (SOC), acidification, and erosion (Fig. 4.5). The preponderance of the impacts on SOM and SOC levels can be related to the climate change challenge, a primary driver for bioenergy development, since soil C sequestration and/or release plays a part in the greenhouse gas balance. Hence, in most studies a variety of more or less complex methods are applied to estimate, at least, variations in carbon stocks, including soil carbon. The climate change impact is a standard "midpoint" impact in LCA, which explains why this method is so widely represented in the corpus. Studies seeking to establish bioenergy sector impacts on climate change frequently rely on impact characterizations from LCA or from a carbon footprint assessment, which is a partial LCA. The use of LCA to characterize impacts in approximately a third of the cases is thus explained by the logical

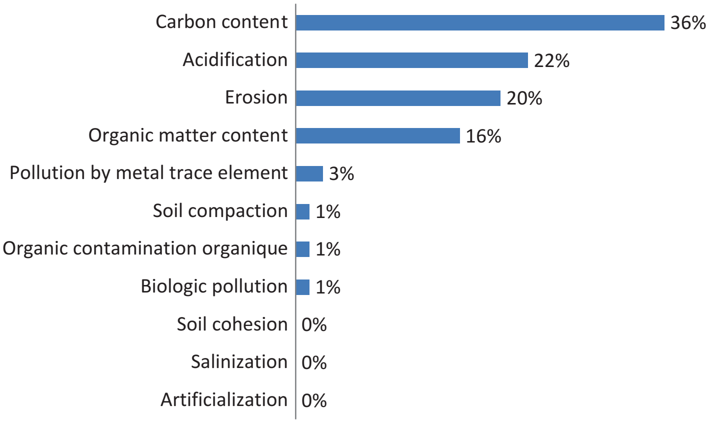


**Fig. 4.5** Breakdown of the subcorpus by type of soil impact considered

connection that may be made between impacts on SOC and the climate change impact. The same is true for the "depletion of fossil resources" impact, another key impact for bioenergy sectors, and to a lesser extent for the impacts of acidification and eutrophication, which are also "midpoint" impacts in LCA that are commonly studied in cases of agricultural production, given the impact contributions of fertilizers. The imbalance in the number of studies across these various impacts arises from the fact that most published LCAs (particularly those related to bioenergy) are partial LCAs, examining only 1–3 impact categories, usually impacts on climate change and the depletion of fossil resources (Bessou et al. 2013). Within the corpus examined here, 22% of LCAs examine only 1 or 2 LCA impact categories, with the climate change impact being the only impact common to all studies.

Erosion, on the other hand, is not a standard impact category in LCA. It can be found in some LCA characterization methods, e.g., LANCA© (Bos et al. 2016) and ACV-SOL (Garrigues et al. 2013), but none of these were used in the articles in the corpus, which is already somewhat dated with respect to recent developments in this subfield of LCA. Erosion is generally regarded as a sensitive impact type for soils, linked primarily to cultivation (conversion of forest into arable land, etc.) or to a change in agricultural practices (change in soil cover, reduced tillage, etc.). It is among the most significant risks for soils. According to the Food and Agriculture Organization (FAO) and the Intergovernmental Technical Panel on Soils (FAO, ITPS 2016), if erosion continues at current levels, it will result in yield losses equivalent to the removal from production of 150 million hectares of agricultural land by 2050. It is thus unsurprising to find erosion among the most studied impacts. Erosion is moreover primarily a physical or physicochemical impact, and one for which a variety of more or less complex models are available. By comparison, our understanding of and the availability of models for assessing other environmental impact mechanisms, especially those involving complex biogeochemical cycles and soil biodiversity, remain a limiting factor in characterizing the impacts of land use and land-use change (LULUC) on soils.

## 4.3.2 *Critical Review of Methods Used for Quantifying Impacts*

### 4.3.2.1 Differences in Carbon Stocks

Calculating impacts on soils with respect to levels of SOM or SOC usually involves evaluating a difference in stored amounts between two or several successive states. Other approaches include *in situ* measurement of fluxes or the use of modeling (see Sect. 4.3.2.3). The difference in stored amounts or "stock-difference" approach is one of two calculation methods recommended by the Intergovernmental Panel on Climate Change (IPCC) guidelines for establishing greenhouse gas emissions at the national level according to the Tier 1 and Tier 2 frameworks (IPCC 2006). The stock-difference approach is thus generally used to calculate greenhouse gas emissions levels and their contribution to climate change, rather than specifically for the assessment of soil impacts. The second method recommended by the IPCC, known as "Gain-Loss," uses a different temporal basis for its calculations but likewise relies on a calculation of differences in carbon stocks. The IPCC stock-difference calculation method is the most widely applied both in the literature and in international standards (British Standards Institute 2011; European Commission 2014; WRI/WBCSD 2011; Bernoux et al. 2010; Colomb et al. 2013; Peter et al. 2016), and is notably that used in Annex V of the European Directive on Renewable Energy (EU 2009/28/EC; Decision 2010/335/EU).

The stock-difference is calculated between two soil uses, assuming that those uses are in place for long enough for organic matter levels to have reached equilibrium. This "necessary and sufficient" duration is set at 20 years as a default, and gains and losses linked to changes in use are linearly amortized over that time period. The net annual change thus ignores both temporary effects and irreversible effects, notably those occurring at or immediately following land conversion.

Stocks are defined for several compartments (aboveground plant material, belowground plant material, SOC, etc.), and depend on initial pedoclimatic conditions as well as on weighting factors linked to the soil-use type and to broad soil management categories describing soil tillage and input levels (low, intermediate, high; with or without organic manures). Soil depths used for measuring soil carbon in the articles in the corpus range from 20 to 360 cm. The median depth is 30 cm, which is the standard depth used in the framework of values provided by the IPCC Tier 1 and the European Directive on Renewable Energies. For Tier 1, default stock values are supplied by the IPCC (IPCC 2006). These default values are used in 11 articles (21% of the total corpus, or 30% of those articles considering an SOC impact, whether or not this is specified in the results), including 10 LCAs (43% of LCA). For Tier 2, measured stock values or values derived from more specific references may be used. In 10 articles (19% of the corpus, or 27% of articles considering the SOC impact), including 3 LCAs (13%), SOC levels are directly measured or come from other references besides the IPCC Tier 1. The other studies considering SOC impact use data from models or do not specify references for the stock values used.

The default amortization period of 20 years to allocate a stock difference to each year of cropping is explicitly or apparently applied in 13 articles (25% of the corpus, or 35% of articles considering SOC impacts). This period can vary in some situations. The rationale for adjusting this parameter may be based on a longer period for returning to equilibrium, e.g., 100 years (Cocco et al. 2014), or on a dynamic specific to a particular type of land use, e.g., a linear amortization over the full length of perennial crop cycle (Mello et al. 2014). Variations in the amortization period may be justified, notably by using context-specific stock values. In some cases, the amortization period is defined by socioeconomic or political criteria, independent of the ecological or agronomic basis, e.g. Kauffman and Hayes (2013). When removed from their original study context, such variations can lead to biases in comparing studies or in seeking to analyze historical LUC impacts.

The advantage of the stock-difference method used in the IPCC Tier 1 lies in its global applicability, with values and coefficients that make it possible to calculate and compare soil carbon levels worldwide or across different types of land use and land management. The disadvantage is the lack of sensitivity to specific management conditions or geographic particularities. A key issue is that the IPCC land use categories do not allow for a precise differentiation of different crop types or rotation types, and the weighting factors only broadly account for the effects of different agricultural management practices, with no way to adjust for the full range of practices constituting a cropping system.

Using the static, non-mechanistic approach underlying the stock-difference method, some studies seek to compare soil carbon levels resulting from different soil use categories, in different locations, but in comparable conditions in order to determine potential LUC impacts at a given moment in time. Levels are compared using a stock-difference approach without necessarily going so far as a full implementation of Tier 2 and application of an amortization period. These synchronic sequences make it possible, in some cases, to construct virtual LUC based on plausible references (Zimmermann et al. 2013; Mello et al. 2014). However, this approach is limited by the availability of such references in comparable conditions for soils sharing the same inherent properties (Bailis and McCarthy 2011; Rasmussen et al. 2012), as well as by the failure to account for hysteresis effects linked to the history of the soil (i.e., the site effect).

The comparison of carbon stocks between natural levels and a given land use type can be expanded across different pedoclimatic and agronomic conditions *via* meta-analyses or statistical studies. Expansion to varied contexts and the inclusion of numerous parameters can potentially give rise to a wide variability of observations and requires multiple datasets for an analysis of determining factors. In the case of eucalyptus in Brazil, for example, a meta-analysis of 89 datasets showed that on average, eucalyptus did not lead to significant changes in SOC compared to natural vegetation, despite non-negligible gains and losses of SOC in certain cases (Fialho and Zinn 2014). By contrast, a statistical analysis of an experimental study based on 135 sites in the South-Central Region of Brazil (~6000 soil samples) found significant average effects from LUC involving the conversion of arable fields, grassland, or *cerrado* into sugarcane (Mello et al. 2014). Depending on the previous use and the number of observations, however, effects were not significant for all soil depths: e.g., after conversion from *cerrado* (5 sites), variations in carbon levels below 30 cm were not significant (Mello et al. 2014). Using a large dataset including LUC over longer timeframes, changes in carbon stocks were analyzed[1] and assembled over multiple time scales in five-year increments and then converted into a "land-use change factor" by soil depth and time period. Values obtained at 30 cm after 20 years corresponded to a complete implementation of the IPCC Tier 2. The different findings of these two studies may arise from real differences between the study contexts, or it may result from a lack of robustness emerging from insufficient sample sizes given the variability of the contexts, practices, and impacts over time and space.

#### 4.3.2.2 Life-Cycle Assessment (LCA)

Life-cycle assessment (LCA) is a standardized methodological framework (ISO 14040 and 14,044, 2006) for multi-criteria assessment of the environmental impacts of a product or service. LCA makes it possible to quantify more than a dozen potential environmental impacts across the entire life cycle of a product, from the extraction of the primary materials through disposal of the product and its residues. This holistic life-cycle assessment approach has become essential, notably for the evaluation of bioenergy sectors, as a way of verifying that the environmental gains relative to fossil fuel use – in terms of carbon emitted into the atmosphere through combustion – are not cancelled out by other impacts, such as increased emissions of other gases during combustion or other emissions and impacts elsewhere in the commodity chain.

To include the whole commodity chain, the LCA must quantify the impacts of all resource uses and emissions at all stages and locations. These contributions are summed up independently of their various origins *via* linear models characterizing a potential final impact, without strong specificity to local circumstances (e.g., environmental sensitivity of the site, threshold effects, etc.). Some models make it possible to weight these different categories based on regionalized factors so as to better account for localized impacts, e.g., an index of water scarcity (Pfister et al. 2009). Nevertheless, LCA impact analyses indicate aggregated impacts calculated in parallel, providing an estimate of potential impacts at the global level.

Acidification impact (terrestrial)[2] as calculated via LCA represents a non-local potential impact for airborne emissions of ammonia, sulfur oxides and nitrous oxides. The relative contribution of the different gases varies according to characterization methods (ReCiPe, ILCD, CML, etc.), and not all methods necessarily

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[1] The statistical approach applied was a linear model with mixed effects.

[2] Some methods also characterize aquatic acidification (e.g. IMPACT+2002), in which other substances are involved (e.g. phosphorous). Due to a lack of precision in some cases, acidification is commonly understood to mean "terrestrial acidification," and was correlated as a soil impact in the experts' analysis of the corpus.

include the fate of the substances in the air. Thus, the acidification impacts reported in the corpus correspond to theoretical impacts linked to the potential for acidification of the different emissions inventoried along the commodity chain. In the case of bioenergy sectors, inventoried emissions relate primarily to the use of nitrogen fertilizers and the combustion of diesel fuel for machinery (Cocco et al. 2014). Impacts are calculated linearly, regardless of the location or timing of emissions, and thus indicate the potential, overall, non-localized impact. The impact pathway leading to actual acidification of a soil takes time, and to date there is no model that allows for quantifying this impact at any given moment or location with the ability to highlight the contributions of a specific production system or activity. Thus, the potential impacts of a bioenergy production chain as determined via LCA provide only a minimal indication of the impacts of biomass crops on the soils and the overall environment directly hosting the crop under study.

The LCA land use impact category with the indicator "Biotic Production Potential" (Brandão and Milà i Canals 2013) is a partial exception to this disconnect from local conditions. The conceptual background to this impact was developed within the framework of thesis research on agricultural LCA (Milà i Canals 2003; Milà i Canals et al. 2007) and in response to a growing awareness, since the early 2000s, of the need to adapt better LCA for agricultural products (the LCA concept was initially developed for industrial products). The importance of soils and soil quality within the analysis of agricultural production drove the scientific community to develop new models for characterizing soil impacts (e.g., Cowell and Clift 2000; Lindeijer 2000; Weidema and Lindeijer 2001). Other methodologies have been developed both within and beyond this conceptual framework for land use impacts, so that today they are more or less complete and accessible (Nuñez et al. 2013; Saad et al. 2013; Garrigues et al. 2013). The LANCA© method (Bos et al. 2016), which is particularly complete, was recently recommended within the context of European harmonization of LCA characterization methods (Vidal Legaz et al. 2013).

These most recent developments are not reflected in the corpus (2001–2014). Of the studies in the corpus, 46% use LCA, 31% consider a soil impact or consider soils as an aspect of an LCA climate change impact, 6%, or just 3 articles, include the land use impact category, and 4%, or 2 articles, include various recent developments related to soil use and soil quality (Saad et al. 2013; Brandão and Milà i Canals 2013; de Baan et al. 2013 *In* Munoz et al. 2014; Helin et al. 2014). The "land-use impact" category is recommended in the European Union Research Center's ILCD[3]'s directives (JRC 2011), albeit with the caveat "to be used with caution". Reservations with regard to this impact category were twofold. The first concern related to the difficulty of implementation due to a lack of specific data on carbon stocks and the need to develop characterization factors on an *ad hoc* basis. These challenges explain the lack of results with respect to this impact category in the literature up to that point. LCA software now includes characterization factors based on default levels from the IPCC (Brandão and Milà i Canals 2013). A second

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[3] International Reference Life Cycle Data System

concern related to the sole focus on soil carbon levels as a way of characterizing impacts on soil quality. Indeed, the land-use impact was originally defined as a proxy for the impact on soil quality of an agricultural or other type of land use. Soil quality is a broad concept that cannot be defined in a single way. Nevertheless, authors agree on the need to consider soil quality with regard to the expected functions to be provided by soils, and the connections between the physicochemical and the biological properties of a soil and its capacity to supply those functions (Doran et al. 2002; Karlen et al. 2003; Kibblewhite et al. 2008). The land-use impact is based on this reasoning and relies on the quantification of changes in soil carbon as an indicator of changes in soil organic matter, itself indicative of significant changes in a soil's capacity to supply various functions, particularly those relating to life and biological development (Milà i Canals et al. 2007). Variations in carbon stocks are thus expressed in terms of the "Biotic Production Potential" indicator. Authors point to the fact that organic matter levels have been shown to be a dynamic soil attribute indicative of various aspects of soil quality, including cation exchange capacity and biological activity (Reeves 1997; Brady and Weil 2002), and are thus the most useful way of evaluating impacts on the life-supporting capacity of soils for agricultural or forestry production, even if other aspects of soil quality also play a role (Milà i Canals et al. 2007).

As currently used in LCA softwares such as Simapro and OpenLCA, the land use impact category uses characterization factors that quantify variations in soil carbon levels based on the values and coefficients proposed by the IPCC[4] (IPCC 2006 Tier 1). As in the use of the IPCC Tier 2, these stock values may be modified by manually adjusting the characterization factors within the LCA software. On the other hand, the conceptual background for the land use impact category is not limited to a strict application of the stock-difference approach. The impact is calculated using two principal reference fluxes, "land transformation" and "land occupation." The first may be included in a "classic" land-use change impact, using a stock difference allocated over 20 years. The second, by contrast, quantifies a theoretical difference in quality relative to a reference state, which will not naturally rebuild itself so long as the land is in use. The definition of initial and reference quality states, which will critically influence fluxes, varies according to the objectives of the study and thus the LCA approach put in place. Initially, the complete conceptual framework also allowed one to take into account additional irreversible impacts or impacts linked to a change in quality directly during the land occupation. In practice, these impacts are not implemented. On the one hand, the use of the IPCC stock values assumes an equilibrium state tied to each type of land use, which does not fit with the calculation of quality-sensitive variations around equilibria during land occupation. On the other hand, irreversible impacts are difficult to identify *a priori* and are generally not considered due to a lack of data and a lack of consensus.

In theory, the land use impact's conceptual framework allows for a more complete characterization of soil quality impacts based on other fluxes connecting changes in soil properties to changes in soil functions. Nevertheless, at present LUC

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[4] According to the stock-difference approach detailed in Sect. 4.3.2.1.

impacts are embedded in land transformation and occupation impacts based on IPCC data, and thus reflect the soil quality impact in terms of soil carbon stock difference only. This stock difference is also used to quantify inventory fluxes for the climate change impact category, although the alignment of these inventory fluxes and impact categories is not always clear.

#### 4.3.2.3 Biophysical Modeling

Approximately 20% of the articles in the corpus make use of mechanistic models to characterize soil impacts. Most of these models are one of two types: those oriented toward the modeling of physicochemical and hydric processes in the soil, with a focus on erosion, water, and SOC levels (including USLE,[5] SWAT,[6] GORCAM, RothC, ICBM, C-Tool, and the Matthews and Grogan model); or more integrative models, including some that aim to provide a full agroecosystem simulation (CROPWAT, MISCANMOD, CENTURY,[7] CERES-EGC, EPIC,[8] SECRETS[9]) or others that attempt to integrate a sector (GREET[10]). These different models can interact, e.g., USLE is used in EPIC, CENTURY is used in GREET, etc. The CROPWAT[11] and MISCANMOD[12] models are not full agroecosystem models because they do not allow for a simulation of losses to the environment.

##### Modeling Specific to Soils

Various models for soil function simulations are used in the corpus. Most are so-called mechanistic or process-based models, although some may also include some empirical correlations. Two principal models are used for modeling the physical and hydric processes in soils, especially erosion risks: SWAT, used in Garcia-Quijano et al. (2005), Babel et al. (2011) Wu et al. (2012), and Hoque et al. (2014); and USLE/MUSLE/RUSLE, used in van Dam et al. (2009), Smeets and Faaij (2010),

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[5] Universal Soil Loss Equation (USLE) http://www.omafra.gov.on.ca/english/engineer/facts/12-051.htm, last consulted January 15, 2017.

[6] Soil and Water Assessment Tool (SWAT) Arnold et al. 1998. A description of this model's parameters (calibration, validation, and performance) can be found in Cibin et al. (2012); a sensitivity analysis can be found in Heuvelmans et al. (2005).

[7] Metherell et al. 1993.

[8] Environmental Policy Integrated Climatic (EPIC) model (Williams 1990), previously known as Erosion Productivity Impact Calculator: http://epicapex.tamu.edu/files/2013/02/epic0509usermanualupdated.pdf

[9] Stand to Ecosystem CaRbon and EvapoTranspiration Simulator (SECRETS) is a mechanistic model for the simulation of forest cover (Sampson and Ceulemans 1999; Sampson et al. 2001).

[10] Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET™): GREET1_2012. http://greet.es.anl.gov/main

[11] FAO: http://www.fao.org/nr/water/infores_databases_cropwat.html

[12] MISCANMOD by Clifton-Brown et al. 2000; Jain et al. 2010.

Secchi et al. (2011), and Debnath et al. (2014). Next in importance are various more or less mechanistic models used specifically to simulate SOC dynamics, i.e. RothC, which is used in two studies (Cherubini and Ulgiati 2010; and Brovkin et al. 2013); and some less widely known models, including the Matthews and Grogan's model (2001), developed specifically for energy crops and used in Styles and Jones (2008) and Mishra et al. (2013); ICBM, used in Tidaker et al. (2014); C-Tool, used in Hamelin et al. (2014); and GORCAM, used in Garcia-Quijano et al. (2005).

USLE and SWAT are the most frequently used models. MUSLE and RUSLE are the "modified" and "revised" versions of USLE, respectively. SWAT is a model designed to assess the long-term effects of land use via the aggregation of units of hydrological response within a watershed. This spatial approach is useful for analyzing the impact of alternative land-use scenarios (Garcia-Quijano et al. 2005). SWAT is widely used,[13] notably because of its flexibility in the choice of calculation methods for evapo-transpiration; the ability to select climate data or have it be generated automatically; the availability of a land use database including a wide range of plant species; and the ability to select different time periods for model outputs for the movement of sediments, nutrients (including four types of nitrogen, total nitrogen, two forms of phosphorous, and total phosphorous), and pesticides (Heuvelmans et al. 2005; Hoque et al. 2014). SWAT is based in part on empirical relationships, some of them from MUSLE, mainly derived from experiments conducted in the United States. Its use outside this area of validation is to be considered with caution (Heuvelmans et al. 2005).

USLE and its later versions are likewise widely used, notably as sub-models within more integrative models such as EPIC. USLE relies on a rudimentary equation to determine waterborne erosion as a product of the erosion risk factors of precipitation (R), soil erodibility (K), length (L) and degree (S) of slope, management of soil cover (C), and anti-erosion practices (P). Parameters R and K nevertheless require datasets based on extended time periods (at least 20 years of continuous climate data) for application in pedoclimatic conditions distant from the initial areas of validity (Devatha et al. 2015). The modified equation MUSLE also takes into account the volume and maximum rate of run-off as well as a factor linked to large soil fragments (Zhang et al. 2010).

### Agroecosystem Modeling

Agroecosystem models such as CERES-EGC (Gabrielle et al. 1998; Goglio et al. 2013; Gabrielle et al. 2014) generally combine several sub-models or modules to enable a modeling of the principal processes acting within and at the interface of the soil-plant-atmosphere compartments. These modules thus allow for the modeling of physicochemical and hydric soil processes, microbial processes and variations in

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[13] SWAT literature database, https://www.card.iastate.edu/swat_articles/, last consulted January 15, 2017.

SOC levels, the development of vegetative cover, and emissions to the environment.

CERES-EGC, used in one article in the corpus (Gabrielle et al. 2014), makes it possible to simulate losses of reactive nitrogen ($N_2O$, NO, $NH_3$, $NO_3^-$) in addition to yields and carbon dynamics. The EPIC models, used in 3 articles (Zhang et al. 2010; Secchi et al. 2011; Debnath et al. 2014), and CENTURY, used in 2 articles (Rasmussen et al. 2012; Dunn et al. 2013), also allow for simulations of agroecosystem functioning, including emissions of nitrogen and phosphorous into the environment. The latter two articles actually only make use of a sub-model within CENTURY relating to SOC dynamics. Besides, the latest versions of the EPIC model also contain routines for simulating SOC that come from CENTURY.

The mechanistic approach requires detailed datasets reporting on the full range of relevant parameters at a sufficiently detailed timescale (e.g., daily). These may be input data (e.g. temperature, precipitation) or fixed parameters determining system properties (e.g., field capacity, variety characteristics) or initial conditions (e.g., level of mineral nitrogen in the soil). Availability of all the necessary data is often a limiting factor in the use of a mechanistic model. In particular, the lack of data for calibrating fixed parameters strongly restricts the use of a model outside its validity domain as initially calibrated. In an example with switchgrass production in Oklahoma, in the United States, the model used (EPIC) could not be calibrated for SOC, with the result that the findings with respect to SOC were not readily useable and, as the authors admit, were not consistent with the literature (Debnath et al. 2014). Similarly, in a study conducted in Iowa on LUC linked to increases in maize acreage based on modeling with EPIC, some data for the soil parameters could not be compiled, leading to a potential underestimation of environmental risks in the five counties considered (Secchi et al. 2011). In another example, in Mozambique, the physiological parameters could not be calibrated for jatropha and thus limited the scope of the CENTURY model for approximating the temporal dynamics of SOC losses (Rasmussen et al. 2012).

Where data are available, mechanistic models make it possible to simulate crop cycles over long timeframes, enabling one to assess the variability and robustness of the results while accounting for inter-annual variations. The corpus includes studies with simulations over 20 years (Gabrielle et al. 2014), 30 years (Secchi et al. 2011; Tidaker et al. 2014), 50 years with 10 climate scenarios (Debnath et al. 2014), and 150 years (Garcia-Quijano et al. 2005). Long-term simulations are particularly important when considering long-term dynamics such as SOC, or in the study of perennial crops. Comparing results from the first and the second crop cycles of eucalyptus in Brazil, for example, revealed notable differences (Fialho and Zinn 2014).

## 4.3.3 Results

### 4.3.3.1 Overview of Impacts Examined

Considering the full range of potential impacts, we can observe that impacts are poorly reported overall (Table 4.2). SOC impacts apart, over 67% of impacts are not reported. It is thus impossible to draw broad conclusions for a given impact type. Nor is there an observable trend with regard to impacts across all commodity chains and LUC types. Of particular note is the fact that levels of SOC and SOM do not show strongly correlated trends, despite the fact that they are intrinsically connected. The lack of information on impacts is potentially at the root of this disjuncture, with (for example) 81% of potential impacts on organic matter levels not studied or not reported. Nevertheless, a more detailed analysis with regard to commodity chains and LUC types is needed to interpret better the slight downward trend of organic carbon levels, and the more heterogeneous results observed for other impacts: acidification, erosion, and organic matter levels.

### 4.3.3.2 Impacts Quantified

Impacts quantified in terms of variations in SOM or SOC (Table 4.3) and erosion (Table 4.4) are reported by commodity chain. Only those scenarios explicitly addressing a bioenergy chain were examined. Among these scenarios, those considering only a change in practice (e.g., export of crop residues) and not a change in land allocation (in the strict sense of a direct or indirect LUC) were excluded from

**Table 4.2** Overview of land use change (LUC) impacts on soils

| *Impact* | *Not reported/not studied/studied but not reported* | *Decrease* | *Stable* | *Increase* | *Variable* |
|---|---|---|---|---|---|
| **Level of organic carbon** | **54%** | 23% | 4% | 6% | 13% |
| **Acidification** | **67%** | 10% | 2% | 17% | 4% |
| **Erosion** | **77%** | 12% | - | 8% | 4% |
| **Level of organic matter** | **81%** | 10% | 2% | 4% | 4% |
| **Trace metallic elements** | **96%** | - | - | 2% | 2% |
| **Compaction** | **98%** | - | - | - | 2% |
| **Organic contamination** | **98%** | - | - | - | 2% |
| **Biological pollution** | **98%** | 2% | - | - | - |

NB: Totals ≠ 100% due to rounding

Cell shading corresponds to percentage totals: Light blue: >15–30%; Gray: >30–45%; Dark gray: >45%

**Table 4.3** Impacts on soil carbon reported in case studies of biomass production for bioenergy (sector × scenario)

| Crop resulting in an LUC | Country species | Level of soil organic carbon (SOC) or soil organic matter | References |
|---|---|---|---|
| Cardoon | Italy<br>*Cynara cardunculus* var. *altilis* DC | Direct LUC from marginal abandoned lands (grasslands: 53.7 t C/ha) to cardoon cultivation (50.3 t C/ha) leads to a loss of SOC. This loss is recovered after 100 years. Soil depth considered: 20 cm. | Cocco et al. (2014) |
| Corn | United States<br>*Zea mays* L. | Domestic LUC primarily involve changes from arable land to corn (50%), from grassland to corn (35%) or from woodland to corn (15%). Orders of magnitude for land area affected by LUC domestically and internationally are similar. International LUC involve conversions of grassland (~ 82%) and reforestation (~ 8%), primarily in Russia. Conversion from forests into corn production (with removal of stover) results in SOC losses of 0.2–0.6 t C/ha/year; from grasslands into corn, in SOC losses of 0.02–0.22 t C/ha/year, and from arable lands into corn in no SOC loss or even a potential gain of 0.12 t C/ha/year. Soil depth considered: 30 cm. | Dunn et al. (2013) |
| | | Direct LUC from conservation grassland (CRP[a]) into corn-soybean or corn-corn-soybean rotations result in average losses of approximately 18.6 t C/ha over 30 years; LUC from CRP into continuous corn result in average losses of approximately 32.2 t C/ha over 30 years. | Secchi et al. (2011) |
| | | Corn cultivation results in a loss of SOC, land use transformation and land occupation impacts combined, of 7 t C/ha/year, with or without removal of stover (theoretical calculations based on the "Land Use" approach and "BPP" indicator of Milà i Canals et al. 2007; Brandão and i Canals 2013). According to FAO statistics and the approach of Milà i Canals et al. 2012, this crop does not lead to LUC. Soil depth considered: 30 cm. | Munoz et al. (2014) |
| Eucalyptus | Brazil<br>*Eucalyptus* spp. | Compared to natural vegetation (forest, grassland, and savanna) across three biomes (cerrado, pampa, Mata Atlântica), eucalyptus plantations result, on average, in a loss of SOC in the top 20 cm of 1.5 t C/ha, but a gain of SOC in the top 40 cm of 0.3 t c/ha. These averages, taken over 50 studies and 39 studies, respectively, are not statistically significant. Average losses over the first plantation cycle are balanced by gains in the second plantation cycle (on average over the 2nd cycle, +2.3 t C/ha at 0–20 cm, and +3.1 t C/ha at 0–40 cm), but again these results are not statistically significant. | Fialho and Zinn (2014) |

(continued)

**Table 4.3** (continued)

| Crop resulting in an LUC | Country species | Level of soil organic carbon (SOC) or soil organic matter | References |
|---|---|---|---|
| Jatropha | India<br>*Jatropha curcas* | Conversion of *Prosopis juliflora* (mesquite) groves into jatropha plantations results in a loss of SOC of 0.5 t C/ha after 4 years. This reduction is not statistically significant. Reduced leaf litter relative to the preceding land use may lead to a more significant loss of SOC over the long term. Soil depth considered: 30 cm. | Bailis and McCarthy (2011) |
| | Mozambique<br>*Jatropha curcas* | Direct LUC from corn (85±14 t C/ha at 0–60 cm) to jatropha (92±7 t C/ha at 0–60 cm) leads to no significant change in SOC. LUC from forest (210±17 t C/ha at 0–60 cm) to jatropha, however, leads to definite losses (modeled with CENTURY at 0.7%/year based on a corn-fallow proxy). Nevertheless, according to the authors, variations in measured SOC levels under forest may be more strongly influenced by soil type than by the LUC. Soil depths considered: 20, 40, 60 cm. | Rasmussen et al. (2012) |
| Miscanthus | Several European countries<br>*Miscanthus* x *giganteus* | Conversion from grassland into miscanthus leads to limited initial losses of SOC (not significant according to the statistical model), followed by an increase, resulting in a net gain already in the first years. Maximum soil depth considered: 60–100 cm. | Anderson-Teixeira et al. (2009) |
| | United States<br>*Miscanthus* x *giganteus* | Domestic LUC primarily involve changes from arable land to miscanthus (96%) or forest to miscanthus (4%). International LUC involve 17 times less land area and are exclusively changes from grassland. A small amount of reforestation is simulated (< 2%). Domestic conversion into miscanthus from forests leads to gains in SOC from 0.1 to 0.18 t C/ha/year, from grassland to gains of 0.38–0.48 t C/ha/year, from arable land to gains of 0.55–0.65 t C/ha/year. Soil depth considered: 30 cm. | Dunn et al. (2013) |
| | | LUC of cultivated lands (all cultivated land in the US without differentiation) into miscanthus results in a potential SOC sequestration of 0.16–0.81 t C/ha/year; or 0.6 t C/ha/year on average across the United States. This result is not compared to initial SOC levels for potentially converted cultivated lands, since this LUC is not explicitly analyzed. | Mishra et al. (2013) |

| | | | |
|---|---|---|---|
| | United Kingdom<br>*Miscanthus* x *giganteus* | Miscanthus cultivation results in an increase in SOC during land occupation relative to the average initial level (+0.62 t C/ha/year) and an opposite virtual impact attributable to the delay in reestablishment of natural vegetation. The total annual impact amounts to a loss of 40.3 t C/ha/year (i.e. the LCA characterization factor within the "Land Use" impact category (Milà i Canals et al. 2007), with 80 t C/ha in the initial state (i.e. arable land), 150 t C/ha at the potential natural state (i.e. warm-temperate forest), and a potential regeneration rate of 0.32 t C/ha/year. Soil depth considered: 30 cm. | Brandao et al. (2011) |
| | France<br>*Miscanthus* x *giganteus* | Conversion of arable land or fallow into miscanthus results in an average increase in SOC of 0.58 t c/ha/year according to a simulation over 21 years with CERES-EGC. | Gabrielle et al. (2014) |
| | Belgium<br>*Miscanthus* x *giganteus* | Conversion of arable land (72% annual crops + 26% permanent grassland + infrastructure) into miscanthus results in a total average increase in SOC of 45.4 t C/ha after a simulation of 150 years. | Garcia-Quijano et al. (2005) |
| | Ireland<br>*Miscanthus* x *giganteus* | Short-rotation miscanthus cultivation results in an increase in SOC of 11.6 t C/ha/year in the case of an LUC from plowed land coming out of fallow, but no change in the case of an LUC from grassland. | Styles and Jones (2008) |
| | | Conversion of arable plowed land or grassland into miscanthus resulted in no significant change in SOC on the observed sites (2 for each type of LUC) 3–4 years after the planting of miscanthus. Following grassland, SOC under miscanthus was sometimes higher than the control (~114 t C/ha > ~81 t C/ha), sometimes lower (~99 t C/ha < ~113 t C/ha). Following plowed land, SOC under miscanthus was slightly higher, i.e. 44–48 t C/ha > 36–39 t C/ha. Plowing history had a significant influence on contrasting SOC levels across the different sites. Soil depth considered: 30 cm. | Zimmermann et al. (2013) |
| Mustard | Italy<br>*Brassica carinata* A. Braun | Direct LUC from marginal abandoned land (grassland: 53.7 t C/ha) into mustard cultivation (44.1 t C/ha) results in a loss of SOC. This loss is restored over 100 years rather than over 20 years as per the default IPCC recommendations (2006). Soil depth considered: 20 cm | Cocco et al. (2014) |
| Poplar | Belgium<br>*Populus spp.* | Conversion of arable land (72% annual crops + 26 % permanent grassland + infrastructure) into poplar plantations results in an average total increase in SOC of 59.7 t C/ha after simulation of 150 years. | Garcia-Quijano et al. (2005) |

(continued)

**Table 4.3** (continued)

| Crop resulting in an LUC | Country species | Level of soil organic carbon (SOC) or soil organic matter | References |
|---|---|---|---|
| Rapeseed | United Kingdom<br>*Brassica napus* | Rapeseed production (with straw returned to the soil) results in a loss of SOC for the duration of land occupation relative to an average initial level (–0.24 t C/ha/year; –0.40 t C/ha/year if straw is removed), and an estimated additional "virtual" impact resulting from the delay in potentially recovering the initial natural vegetation. The total annual impact is equal to a loss of 122.7 t C/ha/year (i.e. the LCA characterization factor within the "Land Use" impact category [Milà i Canals et al. 2007]), with 80 t C/ha at the initial state and 150 t C/ha at the natural potential state (i.e. warm-temperate forest), and a potential regeneration rate of 0.32 t C/ha/year. Soil depth considered: 30 cm. | Brandao et al. (2011) |
| | Italy<br>*Brassica napus* L. var. *oleifera* DC | Direct LUC from marginal abandoned lands (grasslands: 53.7 t C/ha) to rapeseed cultivation (44.7 t C/ha) leads to a loss of SOC. This loss is restored over 100 years. Soil depth considered: 20 cm. | Cocco et al. (2014) |
| | Chile<br>*Brassica napus* L. | Direct LUC from highly degraded grasslands into no-till rapeseed production results in an increase in SOC of 50 kg C/ha/year. This value is based on the use of IPCC Tier 1, adding parts of the gains allocated to the four crops in the rotation. Soil depth considered: 30 cm. | Iriarte et al. (2012) |
| Reed canary grass | Scandinavia<br>*Phalaris arundinacea* spp. | Cultivation of reed canary grass results in a virtual reduction in SOC of 263 t C/ha/year due to the absence of natural vegetation during the land occupation period. The impact from conversion of forest adds a loss of 132 t C/ha/year, whereas conversion of a previously developed area restored to agricultural use results in a restocking of 1432 t C/ha/year, occupation impact included (theoretical calculations based on the "Land Use" approach and "BPP" indicator of Milà i Canals et al. 2007; Brandão and i Canals 2013). Soil depth considered: 30 cm. | Helin et al. (2014) |
| Sitka spruce | United Kingdom<br>*Picea sitchensis* | Use of forestry residues results in no change in SOC during the period of land occupation relative to an average initial level (130 t C/ha) but the total annual impact, including the impact of the delay in reestablishment of natural vegetation, amounts to a loss of 20 t C/ha/year (i.e. the LCA characterization factor within the "Land Use" impact category (Milà i Canals et al. 2007) with 130 t C/ha in the initial state (wood) and 150 t C/ha in the natural potential state (i.e. warm-temperate forest) and a potential regeneration rate of 0.32 t C/ha/year). Soil depth considered: 30 cm. | Brandao et al. (2011) |

| | | | |
|---|---|---|---|
| Soybean | United States<br>*Glycine max* L. Merr. | Conversion of conservation grassland (CRP[a]) dominated by *Bromus inermis* (smooth brome) into no-till soybean production (GMO cultivar 92M91) has no significant effect on carbon levels after one year. However, comparison with lands in corn-soybean production for more than 10 years suggests that these soils hold less carbon and generally show a lower quality index relative to conservation grassland soils. Soil depth considered: 100 cm. | Bhardwaj et al. (2011) |
| | | Conversion of conservation grassland (CRP[a]) dominated by *Bromus inermis* (smooth brome) into no-till soybean production results in a soil carbon deficit of 13.7 t C/ha compared to the potential additional sequestration of such grasslands after 22 years (assuming they are not converted). Soil depth considered: 29 cm. | Gelfand et al. (2011) |
| | Argentina<br>*Glycine max* L. Merr. | Direct LUC from degraded or non-degraded grasslands into reduced-tillage soybean production results in SOC losses of approximately 0.65 and 0.7 t C/ha/year, respectively. Change of species on arable lands is not considered an LUC; nevertheless, according to the IPCC method, shifting to no-till for the same crop results in an increase in SOC (+0.09 t C/ha/year in this case). | van Dam et al. (2009) |
| | | Indirect LUC is supposed to lead to a displacement of the replaced crops to the detriment of natural grasslands. Two displacement scenarios (25% and 50% of the total area involved in the direct LUC) and two calculation methods (total crop or oil-content equivalent) are considered. Indirect LUC thus results in an SOC loss of 0.04–0.35 t C/ha/year. Soil depth considered: 30 cm. | |
| Sugarbeet | France<br>*Beta vulgaris* ssp. | Sugar beet production results in a loss of SOC, land use transformation and land occupation impacts combined, of 7.1 t C/ha/year (theoretical calculations based on the "Land Use" "BPP" indicator of Milà i Canals et al. 2007; Brandão and Milà i Canals 2013). According to FAO statistics and the approach used by Milà i Canals et al. (2012), this crop does not lead to LUC. Soil depth used: 30 cm. | Munoz et al. (2014) |

(continued)

**Table 4.3** (continued)

| Crop resulting in an LUC | Country species | Level of soil organic carbon (SOC) or soil organic matter | References |
|---|---|---|---|
| Sugarcane | Brazil<br>*Saccharum officinarum* | Direct LUC of grasslands into sugar cane production results in a loss of SOC according to IPCC (2006) Tier 1 coefficients. Indirect LUC results in conversion of Amazonian forest into grassland, again resulting in a loss of SOC according to IPCC Tier 1 coefficients. | Alvarenga et al. (2013) |
| | | The authors conclude that direct LUC of arable lands (including grasslands) into sugar cane cultivation has a net zero effect on SOC. However, an LUC from natural cerrado vegetation leads to emissions of 1040 kg $CO_{2eq}/m^3$ ethanol (data are not detailed enough to calculate the impact on SOC). Indirect LUC is included in this study but is based on emissions factors per unit of biofuel as drawn from the literature, and are not specified according to the preceding land use. | Liptow and Tillman (2012) |
| | | Direct LUC of native cerrado vegetation into sugar cane cultivation leads to a significant reduction of SOC at depths of 0–30 cm, on the order of 21 t C/ha over 20 years. The impact below 30 cm is presumed to be not significant. | Mello et al. (2014) |
| | | Direct LUC from grasslands to sugar cane cultivation leads to a significant reduction of SOC, on the order of 6 t C/ha at depths of 0–30 cm over 20 years and 8.7 t C/ha at depths of 0–100 cm over 20 years. | |
| | | Direct LUC from annual crops to sugar cane cultivation leads to a significant increase in SOC, on the order of 10 t C/ha at depths of 0–30 cm over 20 years and 24.6 t C/ha at depths of 0–100 cm over 20 years. | |
| | | Sugar cane production results in a loss of SOC, land use transformation and land occupation impacts combined, of 6.9 t C/ha/year in the North-East and 10.5 t C/ha/year in the South-Central region (theoretical calculations based on the "Land Use" "BPP" indicator of Milà i Canals et al. 2007; Brandão and i Canals 2013). According to FAO statistics and the approach of Milà i Canals et al. 2012, for each hectare of sugar cane, 0.032 ha of forest is indirectly converted. Soil depth considered: 30 cm. | Munoz et al. (2014) |
| | Various countries<br>*Saccharum* spp. L. | Direct LUC from native ecosystems (forest and grassland) to sugar cane production leads to a sharp initial drop in SOC, which will be recovered 60 years after the change in use (using an interval of 100 years). Soil depths considered: 70–100 cm. | Anderson-Teixeira et al. (2009) |

| | | | |
|---|---|---|---|
| Switchgrass | United States<br>*Panicum virgatum* L. | Direct LUC from cultivated land, fallow, or grassland into switchgrass shows a tendency to increase SOC, but data are insufficient for this species to test for statistical robustness. Maximum soil depth considered: 90–360 cm. | Anderson-Teixeira et al. (2009) |
| | | Direct LUC from arable lands into switchgrass leads to SOC storage of 4.42 t C/ha/year; from marginal lands (arid or degraded lands in CRP[a]) into switchgrass, to storage of 3.2 t C/ha/year; and from grasslands, to storage of 0.32 t C/ha/year (values drawn from the literature). | Cobuloglu and Buyuktahtakin (2014) |
| | | Direct LUC from no-till wheat into switchgrass (5 cycles of 10 years of production modeled with stochastic climate data) results in an increase in SOC in all counties modeled (including 3 "land capability classes," with slopes from 0.5% to 4%), i.e. +112.1–531.4 kg C/ha/year. The EPIC model could not be calibrated for SOC, however. | Debnath et al. (2014) |
| | | Domestic LUC primarily involves changes from arable land to switchgrass (92%) followed by woodland into switchgrass (8%). International LUC involves 12 times less land area and are primarily conversions from grassland (~ 90%) and forest (~ 10%). Domestic conversion from forest into switchgrass results in SOC losses of 0.01–0.1 t C/ha/year; from grasslands, in SOC gains of 0.2–0.25 t C/ha/year; from arable lands, to gains of 0.35–0.45 t C/ha/year. Soil depth considered: 30 cm. | Dunn et al. (2013) |
| | Argentina<br>*Panicum virgatum* L. | Direct LUC from arable lands into switchgrass result in an increase in SOC of approximately 0.7 t C/ha/year; from degraded grasslands, the increase is only 0.04 t C/ha/year. LUC from non-degraded grasslands into switchgrass is considered to have no impact on SOC. | van Dam et al. (2009) |
| | | Indirect LUC is thought to result in a displacement of the replaced crops to the detriment of natural grasslands. Two displacement scenarios were considered, corresponding to 25% and 50% of the total area affected by the direct LUC. The indirect LUC thus results in an SOC release of 0.2 and 0.36 t C/ha/year respectively. Soil depth considered: 30 cm. | |
| Temporary grassland | Sweden mixed grasses and clover | Introduction into a cereals rotation of 2 consecutive years of temporary grassland, cut to produce biogas, leads to an annual average accumulation of 0.19 t C/ha compared to 0.02 t c/ha in the initial rotation, according to simulations over 30 years. Soil depth considered: 25 cm. | Tidaker et al. (2014) |

(continued)

**Table 4.3** (continued)

| Crop resulting in an LUC | Country species | Level of soil organic carbon (SOC) or soil organic matter | References |
|---|---|---|---|
| Wheat | France<br>*Triticum* spp. | Wheat production leads to a loss of SOC, land use transformation and land occupation impacts combined, of 9.4 t C/ha/year (theoretical calculations based on the "Land Use" "BPP" indicator of Milà i Canals et al. 2007; Brandão and i Canals 2013). According to FAO statistics and the approach used by Milà i Canals et al. 2012, for each hectare of wheat, 0.016 ha of grassland is directly converted. Soil depth considered: 30 cm. | Munoz et al. (2014) |
| Willow | United Kingdom<br>*Salix* spp. | Cultivation of short-rotation willow results in an increase of SOC relative to an average initial level (+0.14 t C/ha/year) during land occupation and an opposite virtual impact due to the delay in reestablishment of natural vegetation. The total annual impact amounts to a gain of 65.3 t C/ha/year (i.e. the LCA characterization factor within the "Land Use" impact category [Milà i Canals et al. 2007]), with 80 t C/ha in the initial state (i.e. arable lands), 150 t C/ha in the potential natural state (i.e. warm-temperate forest), and a potential regeneration rate of 0.32 t C/ha/year. Soil depth considered: 30 cm. | Brandao et al. (2011) |
| | Ireland<br>*Salix* spp. | Cultivation of short-rotation willow results in an increase in SOC of 0.5 t C/ha/year in the case of LUC from soils formerly plowed and then put in and out of fallow, but no change in the case of LUC from grasslands. | Styles and Jones (2008) |

Quantified results, notably impacts from life-cycle analysis case studies, depend on the boundary of system studied and cannot be repurposed without first verifying their area of validity. Soil depths are only mentioned when explicitly stated in the article or deducible from the methodological approach utilized. The term "grassland" is generally considered to mean "permanent grassland," as opposed to "pasture," which can be understood as temporary grassland where it is associated with the land-use type "cropland," i.e. "arable land"

[a] *CRP* Conservation Reserve Program in the United States

**Table 4.4** Impacts on soil erosion reported in case studies of biomass production for bioenergy (sector × scenario)

| Crop resulting in an LUC | Country species | Erosion | References |
|---|---|---|---|
| Corn | United States<br>*Zea mays* L. | Corn production leads to erosion risks of 13 t C/ha/year with or without removal of stover (theoretical calculations based on the "Land Use" framework [Milà i Canals et al. 2007; Saad et al. 2013]). | Munoz et al. (2014) |
| Eucalyptus | Brazil<br>*Eucalyptus* spp. | Eucalyptus plantations in Brazil (precipitation 1000–2000 mm/year) results in losses by erosion 1–47 t/ha/year for finely or medium-textured soils on slopes of 2–10%; e.g. losses of 8–47 t/ha/year on medium-textured soils on slopes of 6–10% (modeling with USLE). According to data drawn from the literature, eucalyptus plantations have 0.06–0.14 times the erosion risk of seasonal horticultural crops or cereals, and 1–7.14 times the erosion risk of preceding grasslands or forests. | Smeets and Faaij (2010) |
| Manioc | Thailand<br>*Manihot esculenta* Crantz | All conversions into manioc plantations (from forest, rubber trees, orchards, mixed) result in an increase in surface erosion (+9 to 75 %). | Babel et al. (2011) |
| Oil palm | Thailand<br>*Elais guineensis* Jacq. | Conversion of forest or of a mixture of forest/orchard/rubber trees into oil palm plantations result in an increase in surface erosion (+13%). By contrast, conversion of orchard, rubber trees, or a mixture of orchard/rubber trees into oil palm plantations results in a slight decrease in erosion (−1%). | Babel et al. (2011) |
| Poplar | Ukraine<br>*Populus spp.* | Poplar plantations in the Ukraine (precipitation 400–600 mm/year) result in losses by erosion of 0–11 t/ha/year for finely or medium-textured soils on slopes of 2–10%; e.g. losses of 3–15 t/ha/year on medium-textured soils with slopes of 6–10% (modeling with USLE). According to data drawn from the literature, poplar plantations have 0.16–0.22 times the erosion risk of seasonal horticultural crops or cereals and 1.55–11.09 times the erosion risk of preceding grasslands or forests. | Smeets and Faaij (2010) |
| Reed canary grass | Scandinavia<br>*Phalaris arundinacea* ssp. | Production of reed canary grass leads to erosion risks during occupation of 26 t C/ha/year relative to natural vegetation. Impacts linked to the conversion of forest add an erosion potential of 56 t C/ha/year, whereas conversion of developed land restored to agricultural use leads to a reduction in erosion risks of 447 t C/ha/year (theoretical calculations based on the "Land Use" framework [Milà i Canals et al. 2007; Saad et al. 2013]). Soil depth considered: 30 cm. | Helin et al. (2014) |

(continued)

**Table 4.4** (continued)

| Crop resulting in an LUC | Country species | Erosion | References |
|---|---|---|---|
| Soybean | United States<br>*Glycine max* L. Merr. | Conversion of grasslands into no-till soybean production has no significant effect on soil erodibility after one year. The effect is more important over the long term, however (same conclusion as for soil carbon). | Bhardwaj et al. (2011) |
| | Argentina<br>*Panicum virgatum* L. | Direct LUC of arable lands and non-degraded grasslands into reduced-tillage soybeans results in an increase in soil losses to erosion of 2.3 and 2 t C/ha/year, respectively; the same LUC from degraded grasslands results in an increase of 3.2 t C/ha/year. | van Dam et al. (2009) |
| Sugarbeet | France<br>*Beta vulgaris* ssp. | Sugar beet cultivation results in erosion risks of 15.5 t C/ha/year (theoretical calculations based on the “Land Use” framework [Milà i Canals et al. 2007; Saad et al. 2013]). | Munoz et al. (2014) |
| Sugarcane | Thailand<br>*Saccharum officinarum* | All conversions into sugar cane plantations (from forest, rubber trees, orchards, mixed) result in an increase in surface erosion (+10 to 74%). | Babel et al. (2011) |
| | Brazil<br>*Saccharum officinarum* | Sugar cane production results in erosion risks of 3.4 t C/ha/year in the North-East region and 8.3 t C/ha/year in the South-Central region (theoretical calculations based on the “Land Use” framework [Milà i Canals et al. 2007; Saad et al. 2013]). | Munoz et al. (2014) |
| Switchgrass | United States<br>*Panicum virgatum* L. | Direct LUC from arable lands, grasslands, or marginal lands into switchgrass is believed to entirely stop the erosion observed with these land use types. | Cobuloglu and Buyuktahtakin (2014) |
| | | Direct LUC from no-till wheat into switchgrass (5 cycles of 10 years of cropping, modeled with stochastic climate data) results in a reduction of erosion in all counties modeled (with 3 soil classes distributed according to their productive potential and erosion risks; i.e. “land capability classes” with slopes from 0.5% to 4%), equivalent −0.4 to −5.5 t soil/ha/year. | Debnath et al. (2014) |
| | Argentina<br>*Panicum virgatum* L. | Direct LUC of arable lands and degraded grasslands into switchgrass results in a reduction in soil losses to erosion of 4 and 5.3 t C/ha/year, respectively; from non-degraded grasslands, in an increase of 0.5 t C/ha/year. | van Dam et al. (2009) |
| Wheat | France<br>*Triticum* spp. | Wheat cultivation results in erosion risks of 21.9 t C/ha/year (theoretical calculations based on the “Land Use” framework [Milà i Canals et al. 2007; Saad et al. 2013]). | Munoz et al. (2014) |

Quantified results, notably impacts from life-cycle analysis case studies, depend on the boundary of system studied and cannot be repurposed without first verifying their area of validity. Soil depths are only mentioned when explicitly stated in the article or deducible from the methodological approach utilized. The term “grassland” is generally considered to mean “permanent grassland,” as opposed to “pasture,” which can be understood as temporary grassland where it is associated with the land-used type “cropland,” i.e. “arable land” the table. Scenarios not allowing for the individual quantification of soil impacts (e.g., soil carbon separated from total biomass) were likewise excluded.

Out the 52 articles in the corpus, 37 consider a potential impact on SOC, with 26 presenting numerical results that make it possible to identify an LUC and its potential SOC impacts (corresponding to 50% of the corpus or 70% of those articles addressing an SOC impact). Erosion impacts are addressed in an explicitly quantified way by commodity chain in 8 articles (15% of the corpus). The commodity chains most often considered, and in the most detail, with respect to SOC impacts are sugarcane in Brazil, maize and switchgrass in the United States, and miscanthus, primarily in Europe. The most widely considered final product is first- and second-generation ethanol. Results vary considerably by chain, and even within a given chain, depending on the study context and the methods used to characterize the impact, especially with respect to initial stocks and the timeframes considered. Because of the prevalence of the SOC impacts within the corpus as a whole, the mechanisms analyzed (detailed in the following Sect. 4.3.3.3) likewise primarily relate to SOC.

Impacts quantified in terms of acidification are also reported, and are extracted from 5 articles, or barely 10% of the corpus, all of them using LCA (Table 4.5). Nevertheless, contributions to this impact come from various points in the commodity chain, including fertilization for biomass production, transport, transformation, etc., to the extent that it is not always possible to distinguish the specific contribution of the LUC, or even of any step directly linked to the agricultural or forestry phases. Thus, acidification impacts not calculated per hectare are not reported in the table. Besides, although partly linked to earlier phases in the commodity chain (e.g., the production of biomass), the characterization of the acidification impact barely makes it possible to identify impacts on the soil directly where the biomass is grown (see Sect. 4.3.2.2). Biomass crops grown for bioenergy give rise to emissions that can potentially cause acidification, principally by means of the loss of volatile nitrogenous compounds in the production and application of fertilizers and from fuel use for mechanical field operations. At the same time, these emissions may result in an acidification impact elsewhere than on the soil where the biomass is grown.

#### 4.3.3.3 Mechanisms Involved

LUC impacts are the result of interactions between two sets of processes: those attributable to the change in soil cover and associated effects at the soil surface (e.g., erosion, run-off) or below the soil surface (e.g., rooting, infiltration, absorption); and those attributable to management practices associated with the change in land use (e.g. drainage, soil tillage, fertilizer applications, etc.). Some soil impacts are thus intrinsically related to the type of land-use (e.g. a more or less dense vegetation cover, strongly rooted or weakly rooted, annual or perennial, etc.), while other impacts are determined by interactions between the type of land use and management practices (e.g. crop production with or without tillage, crops requiring

**Table 4.5** Impacts on terrestrial acidification reported in case studies of biomass production for bioenergy (sector × scenario)

| Crop resulting in an LUC | Country species | Acidification potential | References |
|---|---|---|---|
| Cardoon | Italy<br>*Cynara cardunculus* var. *altilis* DC | Cardoon production involves emissions of volatile compounds primarily from the production and application of fertilizers (93%), with the remainder coming from fuel combustion for mechanical field operations. These emissions contribute to a potential environmental acidification impact (~37.85 kg $SO_{2eq}$/ha/year). | Cocco et al. (2014) |
| Miscanthus | United Kingdom<br>*Miscanthus* x *giganteus* | Cultivation of miscanthus results in emissions of volatile compounds resulting from the production and application of fertilizers. These emissions, particularly ammonia, contribute to an environmental acidification impact (~6 kg $SO_{2eq}$/ha/year). | Brandao et al. (2011) |
| Mustard | Italy<br>*Brassica carinata* A. Braun | Mustard cultivation results in emissions of volatile compounds from the production and application of fertilizers (89%), with the remainder coming from fuel combustion for mechanical field operations. These emissions contribute to a potential environmental acidification impact (~33.34 kg $SO_{2eq}$/ha/year). | Cocco et al. (2014) |
| Oil palm | Malaysia<br>*Elais guineensis* J. | Oil palm cultivation results in emissions of volatile compounds primarily from the production and application of fertilizers; these emissions contribute to an acidification potential of 4.2 kg $SO_{2eq}$/ha/year. | Silalertruksa and Gheewala (2012) |
| Rapeseed | United Kingdom<br>*Brassica napus* ssp. | Rapeseed production results in emissions of volatile compounds, primarily from the production and application of fertilizers. These emissions contribute to the potential environmental acidification impact (~28 kg $SO_{2eq}$/ha/year). | Brandao et al. (2011) |
| | Italy<br>*Brassica napus* L. var. *oleifera* DC | Rapeseed production results in emissions of volatile compounds from the production and application of fertilizers (89%), with the remainder from fuel combustion for mechanical field operations. These emissions contribute to the potential environmental acidification impact (~30.12 kg $SO_{2eq}$/ha/year). | Cocco et al. (2014) |
| | Chile<br>*Brassica napus* L. | Rapeseed production results in emissions of volatile compounds from the production and application of fertilizers (> 95% of the impact). These emissions contribute to the potential environmental acidification impact (1.9 kg $SO_{2eq}$/metric ton of seed at 92% DM, 49% of which is oil). | Iriarte et al. (2010) |
| Sitka spruce | United Kingdom<br>*Picea sitchensis* | The use of residues results in $NO_x$ emissions from diesel use for machinery. These emissions contribute to a small acidification impact (< 1 kg $SO_{2eq}$/ha/year). | Brandao et al. (2011) |

| | | | |
|---|---|---|---|
| Sunflower | Chile<br>*Helianthus annuus* ssp. | Sunflower cultivation results in emissions of volatile compounds from the production and application of fertilizers ($>95\%$ of the impact amount). These emissions, especially ammonia, contribute to an environmental acidification impact (2.3 kg $SO_{2eq}$/metric ton of seed at 92% DM, 49% of which is oil). | Iriarte et al. (2010) |
| Temporary grassland | Sweden mixed grasses and clover | The introduction into a cereal rotation of 2 consecutive years of temporary grassland, cut to produce biogas, results in a potential acidification impact of 14 kg $SO_{2eq}$/ha/year. This is higher than that of the initial rotation (5 kg $SO_{2eq}$/ha/year) due to higher $NH_3$ emissions resulting from the spreading of digestate from biogas production, notwithstanding reductions in $SO_2$ and $NO_x$ achieved by substituting biogas for fossil fuels. | Tidaker et al. (2014) |
| Willow | United Kingdom<br>*Salix* spp. | Cultivation of short-rotation willow results in emissions of volatile compounds from the use of diesel-powered machinery. These emissions, especially ammonia, contribute to an environmental acidification impact (~2 kg $SO_{2eq}$/ha/year). | Brandao et al. (2011) |

Quantified results, notably impacts from life-cycle analysis case studies, depend on the boundary of system studied and cannot be repurposed without first verifying their area of validity. Soil depths are only mentioned when explicitly stated in the article or deducible from the methodological approach utilized. The term "grassland" is generally considered to mean "permanent grassland," as opposed to "pasture," which can be understood as temporary grassland where it is associated with the land-used type "cropland," i.e. "arable land" different amounts of water or other inputs, etc). The net impact of these complex processes and interactions will depend first of all on the soil type and its properties (see Sect. 4.3.3.3.3), thus limiting the applicability of the observed results to various soils and contexts.

LUC impacts concern first of all the soil resource, but also touch upon other environmental compartments directly or indirectly impacted by soil processes, including water cycling, nutrient cycling, and the movement and transformation of other elements. The mechanisms analyzed in the articles in the corpus primarily consider impacts on SOC.

#### Processes Affecting the Soil Resource

Mechanisms for soil impacts include first of all the physicochemical processes contributing to the loss of soil or of its constituent elements, notably organic matter and nutrients. The most important processes in this regard are erosion and runoff (Brady and Weil 2002). Burning also contributes to the loss of soil organic matter in the case of some LUC. Erosion and leaching of dissolved SOC can account for a large percentage of SOC losses in agriculture, up to 20–30% of changes in SOC (Izaurralde et al. 2007 *in* Zhang et al. 2010). Nevertheless, in the context of a modeling with CENTURY of SOC emissions linked to LUC in the United States, the addition of erosion to the model did not affect emissions (Dunn et al. 2013).

These processes of loss are influenced by changes in land use *via* changes in the vegetation cover, which can play a mechanical role in protecting the soil. The greater average soil cover of perennial crops compared to annual crops reduced erosion risks (Smeets and Faaij 2010). Conversion of grasslands into switchgrass in the lower Mississippi watershed achieved a reduction of erosion and runoff; this reduction was notably correlated with an increase in evapotranspiration and a reduction in the water charge in the watershed (Wu et al. 2012). Forests and perennial crops such as oil palm or rubber tree resulted in less surface runoff thanks to their more extensive root systems and higher evapotranspiration rates compared to manioc and sugarcane (Babel et al. 2011). Losses were also exacerbated in manioc fields because of its limited soil cover (even at maturity), low planting density, and a leaf architecture that accentuated the mechanical action of rain (Babel et al. 2011). These effects were also observed in sugarcane fields compared to grasslands or forests due to periods of bare soil at planting and between harvest and re-growth (Babel et al. 2011). Erosion risks can thus be significant during the initial phase of development following the LUC, until canopy closure; for example in the case of warm-season grasses, like switchgrass, which is slow to establish. These risks can be limited with an appropriate choice of species and the use of improved planting systems (van Dam et al. 2009).

Cultivation activities can also contribute to the physical degradation of the soil, on the one hand, via soil tillage and the destruction of soil aggregates, which can create a soil more susceptible to erosion (Zimmermann et al. 2013), and, on the other hand, via soil compaction, which leads to reduced water infiltration and thus increased erosion potential (van Dam et al. 2009; Smeets and Faaij 2010). Such effects were observed in sugarcane as a result of compaction linked to cultivation operations and harvest (Fiorio et al. 2000; Prado and Centurion 2001 *in* Babel et al. 2011). Increased apparent density and reduced water infiltration, and thus the risk of losses to runoff and erosion were higher where SOC levels were low (Wu et al. 2012). On top of these physicochemical factors are biological processes, which vary depending on soil aeration. Tillage can stimulate processes of decomposition and loss of organic matter linked to increased soil aeration deeper in the soil (Solomon et al. 2001; Zimmermann et al. 2013). Compaction, on the other hand, can lead to anoxic areas in reduced soil pore space, favoring denitrification and hence nitrous oxide emissions.

Changes in land use or land management practices allowing for a protection of the soil surface and an increase in biomass can help maintain or even improve SOM levels. Reduced tillage, notably with the shift from an annual to a perennial crop, and returning crop residues to the soil (including leaf litter with perennial crops) can have a positive effect on the accumulation of SOC (Anderson-Teixeira et al. 2009; Mishra et al. 2013; Zimmermann et al. 2013; Gabrielle et al. 2014; Mello et al. 2014). In the case of conversions to perennial crops, however, reductions in tillage and the maintenance of SOC will vary depending on the type of crop and the type of LUC. In the case of sugarcane in Brazil, for example, the land is usually plowed every 5 years and the sugarcane is replanted. This time span does not necessarily preserve all the carbon stored during the first crop cycle, resulting in net gains where sugarcane followed an annual crop but net losses where it followed grasslands (Mello et al. 2014). On the other hand, the benefits of switchgrass in terms of SOC storage following conversion of arable land or degraded grasslands would persist after 100 years of simulation, although the annual rate was divided by 10 (van Dam et al. 2009).

### Influence of Plant Type on SOC Storage

Increases in SOC are potentially greater with a higher productivity of the soil-plant system. Higher yields and higher above- and belowground biomass production are thus correlated with increases in SOC levels in CENTURY (Dunn et al. 2013). System productivity depends on the land use type and on the match between pedoclimatic conditions and optimum crop conditions. The photosynthetic type (e.g. C3 or C4 plants) is key to the scaling of these optima and of the impact variations across different LUC (van Dam et al. 2009). Overall and relative performances obviously vary depending on location (Dunn et al. 2013; Debnath et al. 2014). In a comparison of two agroecological zones in the United States, various LUC involving the conversion of forests, grasslands, or arable land into maize, switchgrass, and miscanthus resulted in changes in SOC that followed consistent trends but were greater in temperate humid zones ("temperate sub-humid agroecological zone," AEZ10) than in temperate arid zones ("temperate arid agroecological zone" AE2710) (Dunn et al. 2013). Mmetaiscanthus showed highly spatially variable environmental impacts at the level of a region in the Netherlands (Elbersen et al. 2014). Similarly, the potential for SOC storage increased from west to east across the United States as a function of increased soil moisture and associated productivity levels (Mishra et al. 2013). By contrast, in a study of eucalyptus in Brazil, SOC levels did not vary significantly as a function of biome from the cerrado in the center of the country to the pampas in the south or the forests of the eastern coastal region (Mata Atlântica). Annual average precipitation is similar across these biomes (1200–1500 mm), but the length of the dry season differs (Fialho and Zinn 2014). For switchgrass in the United States, studies do not agree on the correlation between biomass production and SOC accumulation (Follett et al. 2012; Mondzozo et al. 2013 *in* Debnath et al. 2014). This example illustrates the complexity of the underlying processes and the need to explore both multiple contexts and other correlated mechanisms.

SOC accumulation most likely depends on both biomass productivity and plant eco-physiology, which determines the allocation of carbon into roots and rhizomes (Anderson-Teixeira et al. 2009; Zimmermann et al. 2013). Hence, the different components of yield, exported biomass, and recycled biomass are not sufficient to understand their influence on SOC. Harvest dates can be chosen to favor leaf senescence and the reallocation of plant reserves into storage organs, and thus potential SOC accumulation; for example by delaying harvest of miscanthus after winter senescence (Mishra et al. 2013; Zimmermann et al. 2013). Root depth also plays a role, as seen in comparisons between sugarcane and miscanthus or switchgrass. SOC accumulation with the latter two grasses was more even, regardless of rooting depth, whereas for sugarcane, SOC accumulation took place primarily at the surface level (Anderson-Teixeira et al. 2009). Fifty percent of the root biomass for miscanthus was found below 90 cm deep (Neukirchen et al. 1999 *in* Mishra et al. 2013). Switchgrass also made it possible to store considerable quantities of SOC by favoring the production of humus, and through the production of a large quantity of rhizomes and root biomass deep in the soil (Lewandowski and Elbersen 2000; Liebig et al. 2005 *in* van Dam et al. 2009).

The impact of recycled biomass depends on interactions between plant type, notably the amount of lignin in the residues, and microclimatic conditions for decomposition. The chemical composition of residues does not fully explain carbon longevity in the soil, which in fact depends on total ecosystem functioning (Schmidt et al. 2011 *in* Fialho and Zinn 2014). In North America, net changes in SOC under switchgrass increased along a positive temperature gradient (Anderson-Teixeira et al. 2009). In Sweden, decomposition dynamics were lower when artificial or temporary grasslands were introduced into annual crop rotations, as the result of a combined effect of the reduction in tillage with drier and colder average conditions during plant growth (Bolinder et al. 2012 *in* Tidaker et al. 2014). Nitrogen fertilizer practices can also alter soil C:N ratios and thus modify decomposition dynamics, as it was observed in the case of LUC toward miscanthus (Schneckenberger and Kuzyakov 2007 *in* Mishra et al. 2013).

### Influence of Soil Type on Variations in SOC and Risk of Losses

Soil properties necessarily play a major role in the capacity of a crop or a vegetation management practice to influence SOC storage or loss. In some cases, inherent soil properties may even mask the LUC effect, as suggested by the authors of a study in Mozambique, in which large variations in SOC under forest outweighed measured variations in SOC under forest versus in maize or in jatropha (Rasmussen et al. 2012).

In the first place, the original SOC level is critical for characterizing the LUC impact. An LUC from grassland to miscanthus can result in a net increase in SOC on mineral soils (Anderson-Teixeira et al. 2009), but a net loss of SOC on organic soils (Elbersen et al. 2014). The magnitude of change in soil carbon levels will thus depend on the reference used to define a soil initial SOC: e.g., a potential level relative to a theoretical natural reference amount (Sect. 4.3.2.2), an initial prior level in the case of an LUC, or a potential theoretical prior level, obtained either by synchronous observation or by comparison with the literature (e.g. Helin et al. 2014). In the case of modeling with CENTURY, the choice of the parameter value for the increase in the rate of SOC degradation associated with cultivation, i.e. the "clteff" (cultivation effect parameter), either as default value or as calibrated for land in maize resulted in increased emissions under maize production but reduced emissions upon conversion to switchgrass or miscanthus, due to the reduced SOC levels prior to the LUC (Dunn et al. 2013).

At the same time, soil texture and structure also play a role in mechanisms of SOC storage and loss. Soil clay content, for example, was shown to moderate SOC gains under perennial crops and losses under maize in a study covering several countries (Anderson-Teixeira et al. 2009). In the case of eucalyptus in Brazil, clayey soils tended to store more SOC than sandy soils, particularly in the top 20 cm of the soil profile, although the results were not statistically significant (Fialho and Zinn 2014). Retention of SOC in sandy soils in Brazil was mainly linked to unstable debris, which may be maximized and stabilized with specific practices in order to increase SOC over the long term (Fialho and Zinn 2014). This type of large-particle organic matter, distinct from soil organo-mineral complex, is more sensitive to mineralization than organic matter bonded to silt and clay. Thus, a study in Tanzania found that soil texture influenced the change in the type of organic matter present in the soil following an LUC of degraded woodland into annual crops, notably via amino sugar signatures. Microbial sugar metabolites are more stable and were less affected by this LUC in more finely textured soils (Solomon et al. 2001). Other properties, notably soil aggregates and levels of iron and aluminum oxides, were shown to strongly influence SOC dynamics and retention in Brazilian Oxisols (*in* Fialho and Zinn 2014).

A group of soil parameters relating to the productive capacity of soils was used in the United States to define classes of soil capacity, or "land capability classes." In this system, soils with a similar, sustainable productive capacity with respect to a specific pedoclimatic and agronomic context are classed together. Criteria include parameters for the morphology, structure, texture, and mineral composition of soils.

In the case of an LUC from no-till wheat to switchgrass, modeling studies suggested an increase in SOC and a reduction in losses of soil, nitrogen, and phosphorous across the three soil classes considered (land capability classes I, II, and III). The higher the initial loss risk through erosion and runoff, the larger the potential reduction in losses: thus, type I soils having the lowest risk of erosion showed the smallest reduction in losses; type III soils having the highest risk of erosion showed the greatest reduction in losses; type II soils were intermediate in both respects. SOC storage was more significant for type I soils, however, given their higher productive potential and a greater associated SOC storage compared to the type II and type III soils as modeled (Debnath et al. 2014).

#### Indirect Impacts

Erosion, runoff, and leaching can result in losses of nutrients into the environment (Babel et al. 2011), potentially leading to a eutrophication impact on wetland environments. Such losses are influenced by both LUC and practices. The expansion of manioc and sugarcane production in the Khlong Phlo watershed in Thailand might lead to greater losses of sediment, nitrate, and phosphorous than those caused by oil palm production due to increased risks of erosion and runoff. On the other hand, at a similar erosion and runoff risk level, oil palm could lead to greater losses than rubber plantations or orchards due to more intensive fertilization (Babel et al. 2011). Miscanthus, in another context, resulted in less nitrate loss compared to annual crops of oilseed rape, sugar beet, and wheat in the region of the Ile de France by a factor of 1.05–4 (Gabrielle et al. 2014). Switchgrass was observed to lead to lower losses via runoff of nitrogen (up to 68.5 kg $N.ha^{-1}.year^{-1}$ less) and phosphorous (up to 1.5 kg $P.ha^{-1}.year^{-1}$ less) when compared to wheat on various sites in Oklahoma, in the United States. Again in the United States, in Indiana, miscanthus and switchgrass were found, through modeling work, to result in lower losses of sediments (up to 30% less), total nitrogen (up to 16% less), and total phosphorous (up to 33% less) when compared to a previous land use of grassland, maize-soybean rotation, or a mixture of the two. Loss reductions were comparable between miscanthus and switchgrass with the exception of nitrogen losses, which were slightly higher in miscanthus than switchgrass despite equivalent inputs of nitrogen fertilizer (Hoque et al. 2014). In Iowa, the conversion of grassland areas from Conservation Reserve Program into maize monoculture or maize in rotation led in all scenarios to increased losses of sediments, phosphorous, and nitrogen into the environment (Secchi et al. 2011).

Nitrogen fertilizer inputs are likewise accompanied by direct and indirect emissions of volatile nitrogen compounds into the atmosphere, which can contribute notably to climate change and acidification impacts. These impacts, as described above in particular for acidification (see Sect. 4.3.2.2), can also have indirect impacts on the soil. In the northern part of the Netherlands, the replacement of crop rotations with miscanthus would lead to a reduction of such emissions and subsequent impacts due to the relatively low levels of inputs (Elbersen et al. 2014). In

Ile-de-France, the same LUC of annual crops to miscanthus would result in similar reductions in these emissions. Emissions of $N_2O$ would be 2–6 times lower compared to those for crops of oilseed rape, wheat, and sugar beet; those of NO would be divided by 2, and those of $NH_3$ by 14–32 (Gabrielle et al. 2014).

Finally, compared to annual crops, the higher evapotranspiration rates of perennial crops – as observed for eucalyptus, poplar, and switchgrass – could reduce runoff and associated nutrient losses (see Sect. 4.3.3.3.4), although this also implies a potential reduction in available water resources (van Dam et al. 2009; Smeets and Faaij 2010; Wu et al. 2012).

## 4.4 Discussion and Conclusion

Although soils are the first resource impacted by land use and land-use changes, the characterization of the impacts on soils and soil quality remains limited, both in terms of the number of articles addressing the subject and in terms of the properties and parameters that have been explored to assess effects on soil quality. Barely 20% of the articles in the corpus addressed soil impacts (52 out of 241) and only 15% quantified these impacts (37 out of 241). Within this limited sample of 37 articles, 70% detailed impacts on SOC; 22% also addressed erosion impacts or erosion only (1 article). The dominant focus on SOC impacts is explained by the critical role played by SOM in the capacity of a soil to fulfill various functions. SOC levels, which are directly correlated with SOM levels, thus act as an indicator reflecting a variety of potential changes in the properties and functions of soils. Besides, SOC is also a relatively easy parameter to measure.

Overall, the studies in the corpus show that perennial plants tend to be better at maintaining and even improving SOC levels compared to annual crops. Nevertheless, quantified results are highly variable and depend on the pedoclimatic and agronomic context. Some results show variations in SOC that are more or less sensitive to soil type. Detailed analysis of the influence of soil type would require large meta-analyses or studies based on exhaustive measurement protocols across numerous field sites. This type of study is poorly represented in the corpus, which for this reason offers relative little robust information as to the influence of soil type on soil impact mechanisms resulting from LUC.

Experimental and modeling results have shown the importance of history and evolution in LUC – that is, the importance of considering change over time from a point of equilibrium prior to the LUC and depending on the plot history up to a new point of equilibrium. Nevertheless, many studies rely on default reference values; e.g., 30% of studies quantifying LUC make use of coefficients from the IPCC Tier 1 (2006). The significance of a change in SOC in terms of impacts on soil quality is only demonstrable if that change does result from modifications in soil processes. The use of the static stock-difference method based on default coefficients is an uncertain proxy for soil impacts, particularly if the land uses to be compared are not at equilibrium in terms of soil properties and functions. Taking into account the dynamics of change in SOC using a modeling approach based on these processes seems unavoidable. Analysis of these dynamics requires a more holistic approach both to SOC itself (i.e., at different soil depths, in various soil organic matter fractions, etc.) and to the interactions between SOC and other soil parameters and soil properties, notably connections to the carbon and nitrogen cycles, biological activity, etc. Much research is needed to improve these models: on the one hand, some models still use default parameters that are not necessarily calibrated for all pedoclimatic conditions, potential uses, and LUC (e.g. Goglio et al. 2015); on the other hand, not all the processes involved in variations in soil quality are fully understood (Brady and Weil 2002).

LUC impacts on SOC are overall more thoroughly researched than other impacts relating to soil quality. Although this indicator could be still much improved, other impacts also need to be examined more closely and potentially better integrated into existing models. The study of some perennial crops has suggested a potentially antagonistic effect between the maintenance of soil quality (via increases in SOC and the reduction of erosion and runoff risks) on the one hand, and impacts on water resources on the other hand. This dilemma hints at the necessary tradeoffs and compromises that can be involved in multi-criteria assessments. The various impacts on soils must be analyzed in parallel with other impacts, e.g. on water (Bispo, Chap. 5, this volume) and biodiversity (Gaba, Chap. 8, this volume) The processes at work within the different environmental compartments influence a full suite of resources and are interconnected via geochemical cycles (carbon, nitrogen, water) and via changes in biological habitats. LUC for energy crops can also displace food crops. In these situations in particular, but also in the broader context of sustainable development, tradeoffs between different crops must be considered also with respect to their socioeconomic impacts.

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## Chapter 5

# Review of the Impacts on Water of Land-Use Changes Induced by Non-food Biomass Production

**Antonio Bispo**

**Abstract** The expansion of crops grown solely for energy production results in land-use changes that in turn carry environmental consequences, notably for water resources. By means of a review of the literature, we analyzed the causal chain linking the expansion of perennial and annual crops destined for bioenergy (heat, electricity, fuel), to land-use changes (direct and indirect), and then to impacts on the quantity and quality of water. Fifty-four articles were identified. The majority of research since the end of the 2000s relates (in equal amounts) to first-generation or second-generation biofuels, although other forms of bioenergy, for example for heat or electricity, have also received some attention. The most frequently studied production areas are in North America (mainly in the USA), South America, and Europe, all regions where public policies have encouraged the development of biomass crops. Direct and indirect land-use changes considered relate primarily to the conversion of forests and grasslands into annual crops, and secondarily to the establishment of perennial crops to replace annual crops. The most frequently studied impacts are those relating to water consumption and eutrophication, usually at the regional level. Methodologies are rarely based on data collected in the field, but instead make use of biophysical modeling to generate projections, or adopt multi-criteria approaches of the life-cycle analysis type. Given the range of different climates, geographic zones, biomass types, and research methods involved, it is difficult to draw firm conclusions, but it would appear that second-generation biofuels have less of an impact on water resources than other forms of bioenergy.

**Keywords** Biofuels · Bioenergy · Biomass · Land-use change · Water consumption · Eutrophication

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## 5.1 Introduction

Several countries throughout the world (e.g., the USA, many European countries, Brazil) have enacted ambitious energy policies favoring biomass as a way of reducing their petroleum dependence and greenhouse gas emissions (Afiff et al. 2013; Sorda et al. 2010). Biomass crops, both annual and perennial, can be used to produce heat, to make first-generation biofuels (using the storage organs to produce oils or to make ethanol after fermentation of the sugars), or to make second-generation biofuels (e.g., using crop residues or wood, with the sugars extracted by alcoholic fermentation). The greenhouse gas budget for these crops was initially considered to be neutral, since the burning of these biomass-based fuels would only release as much $CO_2$ as had been captured during their growth.

At the end of the 2000s, however, this idea was challenged by several studies seeking to account for the land-use changes resulting from the expansion of energy crops (e.g., Fargione et al. 2008; Searchinger et al. 2008).

Financial incentives and increased demand for biomass for non-food uses can lead to an increase in land area devoted to such crops, to the detriment of permanent grasslands and forested areas. These land-use changes are considered *direct* since they replace a natural area (such as unmanaged forest) or a managed natural area (such as permanent grassland) with energy crops. Indirect land-use changes occur when crops initially destined for food or feed are instead used for energy production (as in the case of first-generation biofuels) and, in a context of increasing global food demand, food or feed production must be shifted elsewhere, thus resulting in the conversion of natural areas. The expansion of energy crops can thus create a cascade effect, displacing crop production onto previously uncultivated areas.

Given the climate argument, the global literature has focused heavily on the greenhouse gas implications of energy crops (Bamière and Bellassen, Chap. 6, this volume), but land-use changes have other consequences as well, including impacts on water movement and water quality. Converting natural areas for crop production or allowing agricultural lands to become forested will necessarily alter the water resources conditions, with respect to both quantity (e.g., irrigation, run-off, loss of infiltration, evapotranspiration) and quality (e.g., eutrophication, contamination). These modifications can be measured at the field or farm level (Bhardwaj et al. 2011), at the watershed level (Donner and Kucharik 2008; Costello et al. 2009; Delucchi 2010; Ng et al. 2010; Babel et al. 2011; Wu et al. 2012; Sarkar and Miller 2014), at the national or major regional level (Davis et al. 2012; Vanloocke et al. 2010; Hernandes et al. 2014; LaBeau et al. 2014; Gabrielle et al. 2014) or at the global level (Hill et al. 2006; Dominguez-Faus et al. 2009; Gerbens-Leenes et al. 2012; Beringer et al. 2011).

The goal of this article is to present the results of a systematic review of scientific research assessing the quantitative and qualitative impacts on water of land-use change resulting from the production of non-food biomass. This summary describes the types of biomass, final products, land-use changes, and impacts on water resources considered by the literature on non-food biomass production. In addition, we will review the methods and results of these studies and discuss the major trends that emerge from the literature as a whole.

## 5.2 Literature Review Methodology and Description of the Corpus

Using two databases (the Web of Science and CAB), an exhaustive literature review was conducted on the subject of land-use change from 1975 to 2014, resulting in the identification of approximately 5700 articles. All of the references included keywords related to land-use change (e.g., land-use change/allocation/conversion, land sparing, marginal land); a further requirement was applied to the effect that all articles must consider the following causal sequence: reorganization linked to a policy directive (e.g., energy policy), land-use change (direct or indirect), and environmental impact (e.g., LCA, climate, eutrophication, biodiversity, resource consumption).

An automated analysis of titles, abstracts, and keywords enabled the identification of a group of themes structuring the corpus (El Akkari et al., Chap. 2, this volume). The subset of articles addressing land-use changes linked to agricultural reorganization for energy production (1785 references) was reviewed by a dozen researchers with expertise in the field, who selected the most relevant 241 articles. These were then analyzed using a standardized reading grid (Réchauchère et al., Chap. 1, this volume) to describe the objectives, methods, and impacts for each article. Figure 5.1 summarizes this methodology, specifying the number of articles selected at each step in the process.

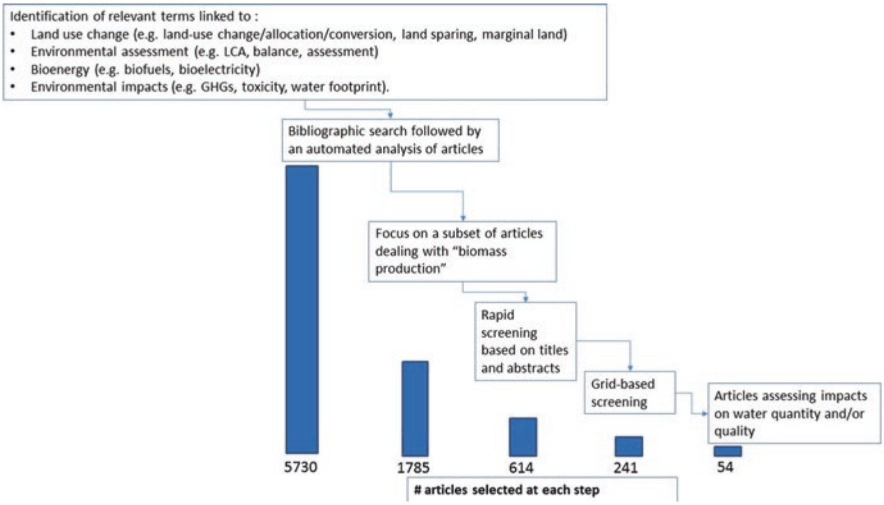


**Fig. 5.1** Steps in article selection and number of articles selected at each step

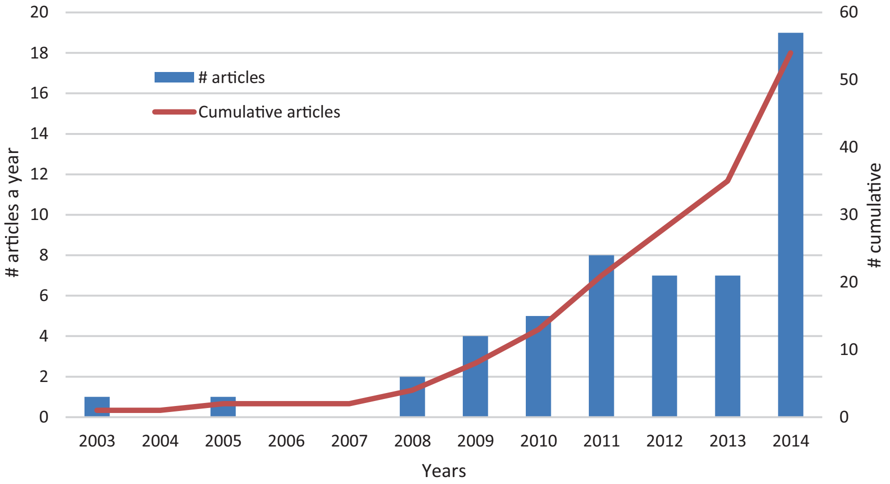


**Fig. 5.2** Year of publication for articles studying impacts on water of land-use change related to non-food biomass crops

Here we will examine the 54 articles (Fig. 5.1) assessing impacts on water quantity and/or quality of land-use change related to non-food biomass production. This subset of the corpus included 22.7% of the initial group of articles. Impacts on water became a major focus of study after 2008, and expanded steadily through 2014 (Fig. 5.2). No articles were found on this topic from 1975 to 2002.

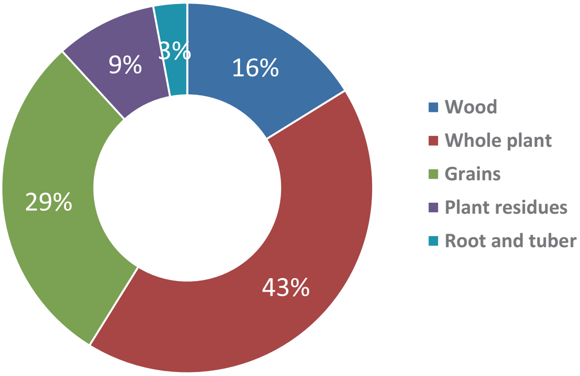
While this may appear to be a relatively modest number of articles, it should be noted that within a single article, the authors often examine several hypotheses with respect to crops and impacted environments, thus yielding several scenarios per article (combinations of "crop x altered environment x resource impact"). In total, the 54 articles account for 121 land-use change scenarios.

## 5.3 Sources, Characteristics, and Uses of Non-food Biomass Production in the Selected Articles

This section describes the types of biomass employed for bioenergy and biomaterial production and the major use categories for biomass output (e.g., fuel, electricity, heat, materials). It also summarizes the geographic areas and levels of focus for the studies reviewed.

The most important biomass materials considered were grains (29%), whole plants (43%), and to a lesser extent wood (Fig. 5.3). Considering the significant percentage of biomass used for biofuels (Fig. 5.5), we can speculate that "grains" were generally being used to produce first-generation biofuels (29% of the articles selected), while "whole plants" or "wood" were destined for second-generation

**Fig. 5.3** Plant parts utilized (% of articles)



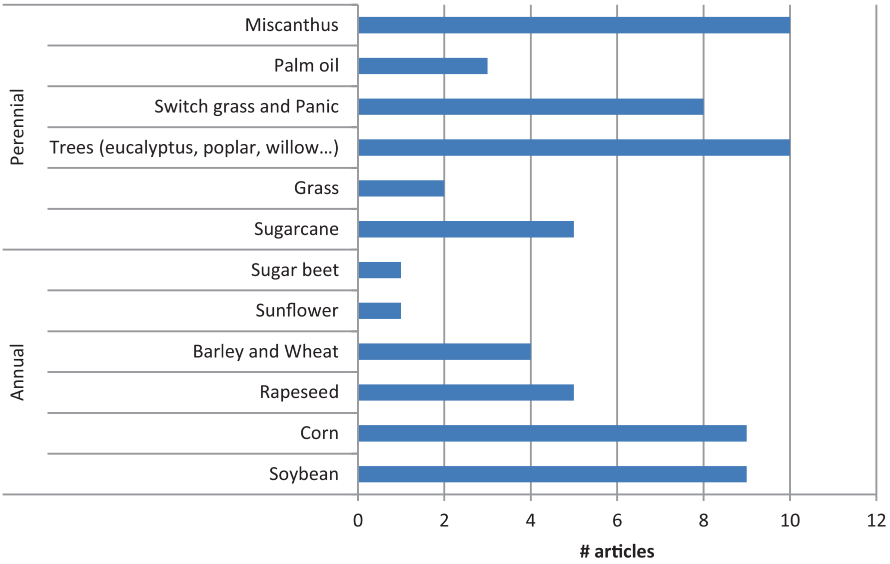


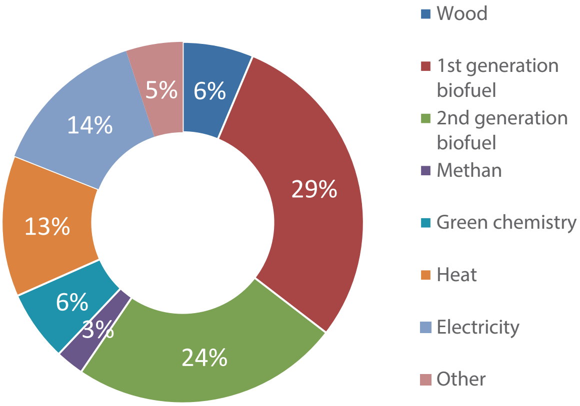
**Fig. 5.4** Species considered within the 54 articles (a single article may consider multiple species)

biofuel production (24% of uses), or for the production of heat or electricity (13% and 14% of uses, respectively).

The most important species studied were perennial species (38 articles), including various woody species (e.g., eucalyptus, short-rotation coppicing of willow or poplar), miscanthus, and switch grass. Sugarcane and oil palm are less frequently considered. Among annual crops, the majority of work has been done on corn and soybeans, with other species, such as sugar beet, less widely studied (Fig. 5.4).

In the articles addressing impacts on water, the majority of biomass was destined for biofuel production (53%), either first or second generation, or for electricity or

**Fig. 5.5** Destined use of non-food biomass (% of articles)



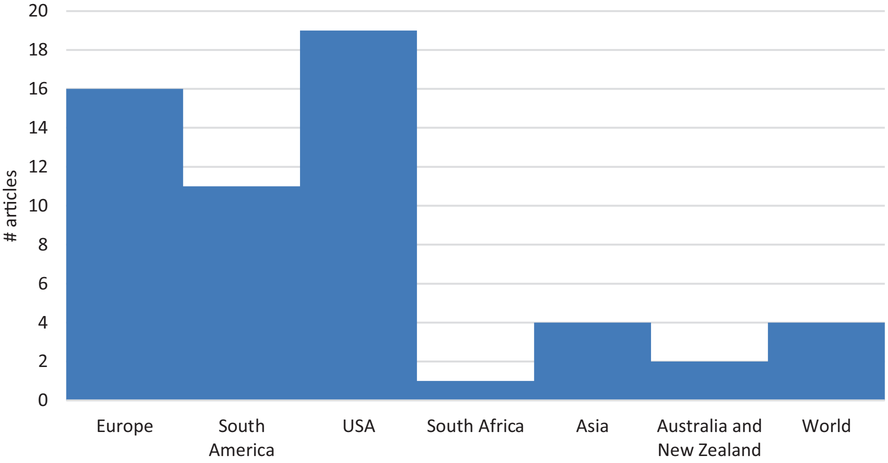


**Fig. 5.6** Location of reorganization by major world region

heat (27%). The impact on water resources of other biomass uses (e.g., in the production of materials or in green chemistry) is less well documented (Fig. 5.5).

When specified (that is, in about a third of the articles considered here), the cause of the observed reorganization toward non-food biomass production is most often attributed to public policies such as the EU directives on biofuels and renewable energy or analogous energy policies in the US (Sorda et al. 2010).

The most frequently studied areas of production were in North or South America (over 50%) or in Europe (28%) (Fig. 5.6). A handful of studies (4) did not focus on a specific geographic area but instead sought to consider total global land area.

Countries where impacts on water resources of agricultural reorganization linked to bioenergy development are being studied are, in descending order of importance:

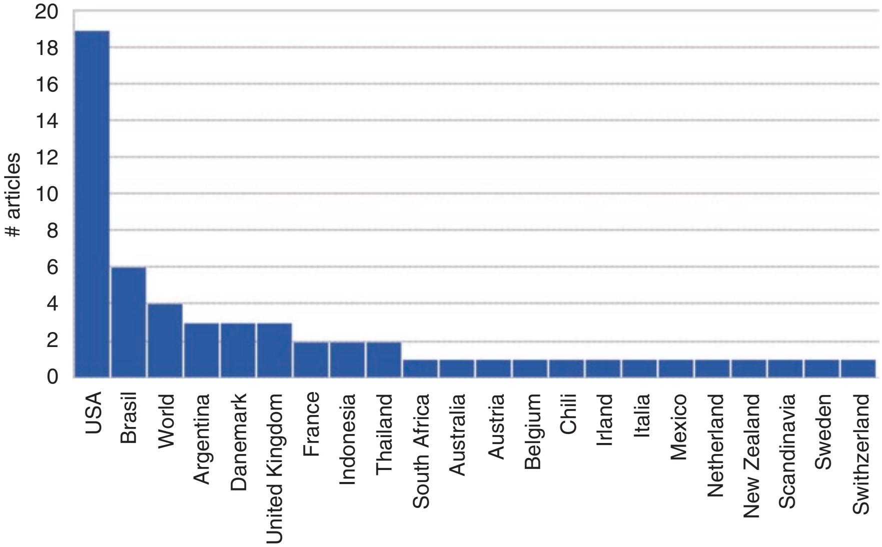
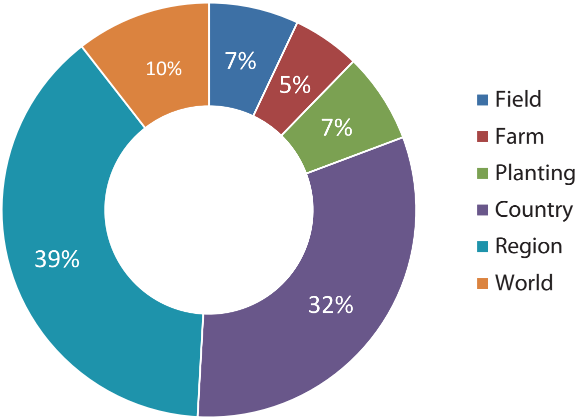


**Fig. 5.7** Location of non-food biomass production in the 54 articles

**Fig. 5.8** Level of spatial analysis in the selected articles (% of articles)



the USA (40% of articles), Brazil, Argentina, Denmark, the United Kingdom, France, Indonesia, and Thailand (Fig. 5.7).

Spatial levels considered in the 54 articles correspond primarily (in nearly 70% of the articles) to the level of the country or large region (for example, a US state or a watershed) (Fig. 5.8). Some studies also considered smaller spatial levels such as a planting, field, or farm (in total, these represented less than 20% of the articles examined). Studies focusing on the global level are relatively rare (10% of the articles).

## 5.4 Land-Use Changes in the Selected Articles

This section describes and analyzes environmental transformations or changes in land use resulting from the expansion of non-food crops. The authors of the surveyed articles generally test multiple hypotheses with respect to environmental modification *via* the introduction of non-food crops, leading to the definition of multiple scenarios with potentially widely different impacts on water resources. Impacts of direct land-use changes (dLUC) are more frequently considered (88 scenarios) than indirect effects (iLUC) (33 scenarios). These two types of LUC are described below.

### *5.4.1 Direct Land-Use Change*

Figure 5.9 shows the types of land-use change most frequently considered in the scenarios presented within the sub-corpus. The most commonly described dLUC involve forests converted to perennial or annual crops (in 12 and in 7 scenarios, respectively), annual crops converted to perennial crops (in 22 scenarios), and grasslands converted to perennial or annual crops.

Figure 5.10a confirms that grasslands, arable crops, and forests are the primary land-use types affected by direct land-use change. In these scenarios, these land-use

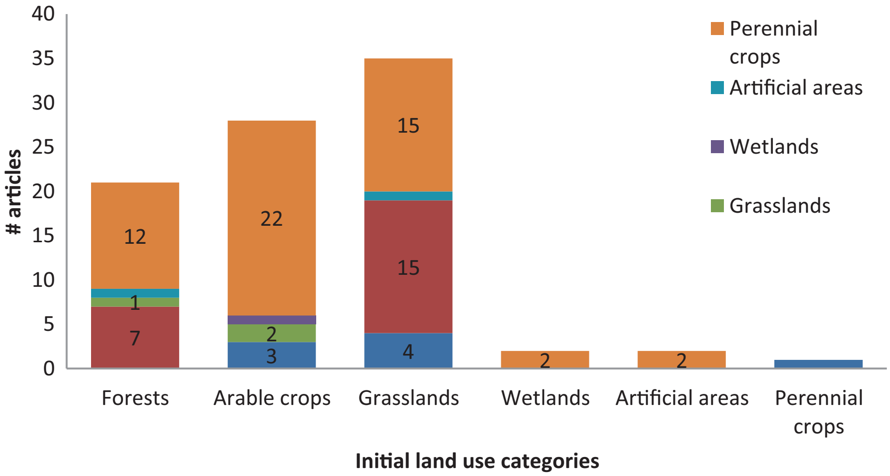
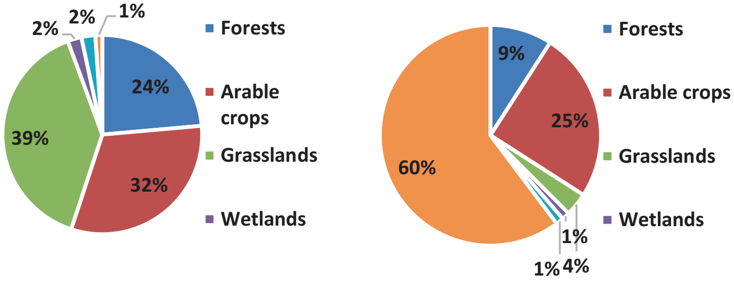


**Fig. 5.9** Principal land conversions examined (direct LUC)



a. Initial Land category type

b. Land Use category created

**Fig. 5.10** Land use categories modified (**a**) and land use categories created (**b**) by direct LUC in the 88 scenarios in the 54 articles (% of scenarios)

types are primarily converted to perennial crops (60% of scenarios, a strong majority) or to arable crops (25% of scenarios) (Fig. 5.10b). It is interesting to note that the conversion of natural areas (e.g., wetlands) has been very little studied.

## *5.4.2 Indirect Changes in Land-Use*

Overall, similar conclusions appear for iLUC as for dLUC. Land-use types impacted by indirect land-use change include forests and grasslands, usually converted to annual or perennial crops. Annual crops are less often affected (only six scenarios). Indirect LUC apply primarily to changes in forested environments (Fig. 5.11), however, whereas dLUC relate above all to changes in grassland (Figs. 5.9 and 5.10a). The scenarios involved are highly diverse. In some scenarios, a crop species initially intended for food use is instead used for energy (e.g., corn, soybeans, rapeseed), with the food production then shifted to other land areas (e.g., forests or grasslands). In other scenarios, energy crops are established on existing grasslands (e.g., miscanthus), and new pastures are created on land areas previously occupied by forest.

For those articles that specify a geographic area (10 out 54), the scenarios for which iLUC are examined relate to the global level (4 articles) or to South America (4 articles).

Figure 5.12a, b confirm that it is indeed forests (43%) and grasslands (36%) that are most often converted when iLUC are studied, and that these uses are in great majority replaced by perennial or annual crops (82%).

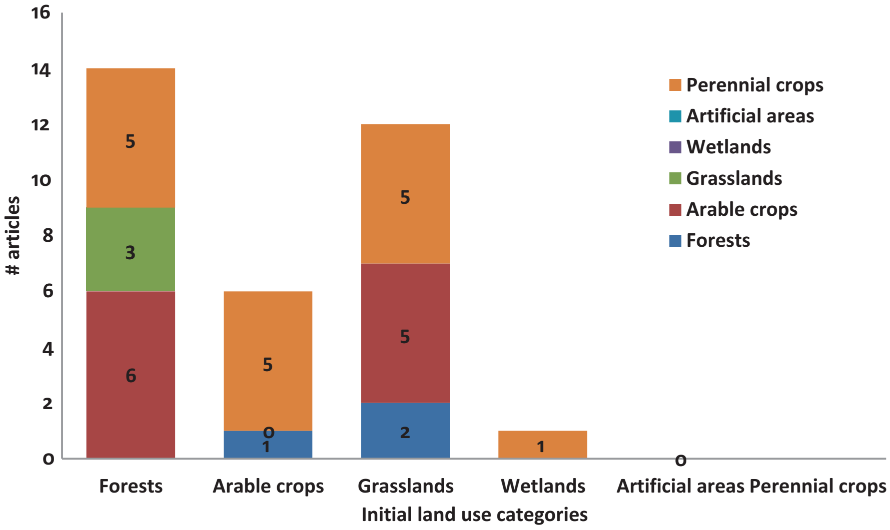
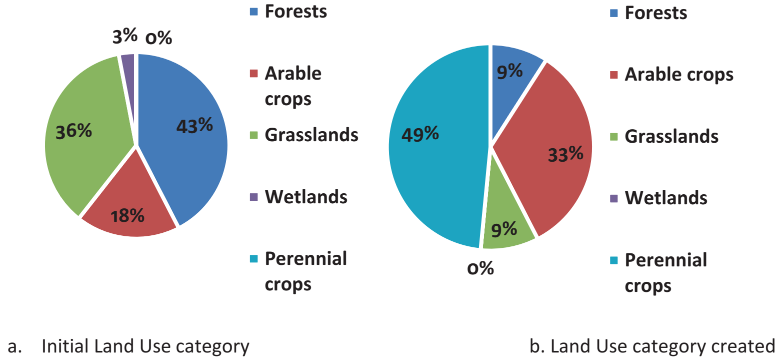


**Fig. 5.11** Principal transformations studied (indirect LUC)



a. Initial Land Use category

b. Land Use category created

**Fig. 5.12** Land-use categories modified (**a**) and land-use categories created (**b**) by indirect LUC in 33 scenarios within 54 articles (% of scenarios)

## 5.5 Evaluation of LUC Impacts on Water in the Selected Articles

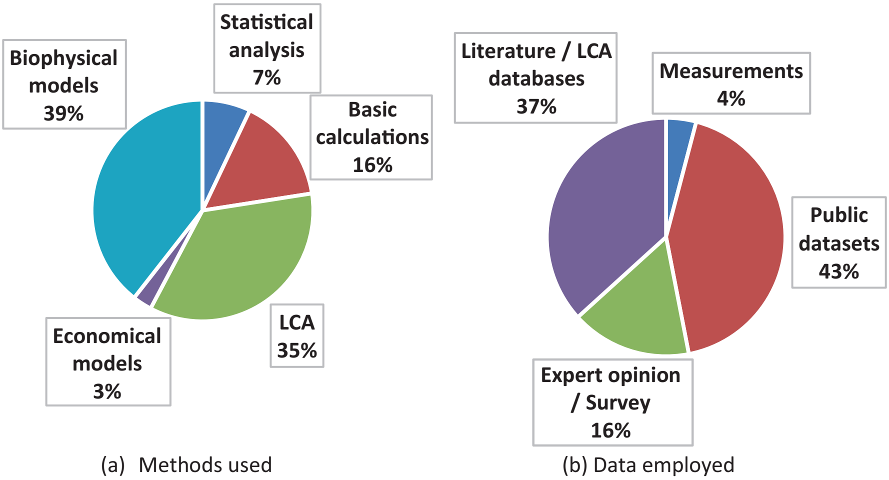
Several methods are used to evaluate the impacts on water of land-use changes connected to the development of bioenergy. These methods rely on a range of different types of data, from a variety of sources, to calculate impacts on water resources (e.g., water use, water pollution, changes in water flow). Impacts are generally calculated at the level of the country or the region, or in some cases at the level of the field or the planting.

### *5.5.1 Methods and Data Used to Evaluate Water Impacts*

The most frequently used methodologies are life-cycle analysis (LCA) and biophysical modeling (Fig. 5.13a). Some studies use established values for factors such as water consumption or eutrophication, for example, based on the land area affected and the species under cultivation (this is termed a "basic calculation" approach). Nine articles out of the 54 mention the use of uncertainty analyses or sensitivity analyses (through the use of Monte Carlo simulations, for example). Methods relying on economic models (3%) are under-represented with respect to impacts on water resources relative to their use with respect to other impacts, such as on climate, where they are used in 20% of the articles (Bamière and Bellassen, Chap. 6, this volume).

The biophysical models employed range from the very simple, simulating one or several processes (e.g., water retention, loss of organic matter, plant nutrition), to the more complex (e.g., water dynamics in the soil-plant-atmosphere-aquifer system). Among the latter, the three most frequently used models (12 articles in total) are EPIC (Environmental Policy Integrated Climate), SWAT (Soil and Water Assessment Tool), and Agro-Ibis. Results from the models are sometimes used as starting-point data for the completion of an LCA.

Less than 5% of the studies surveyed make use of observational or experimental data to evaluate the impact of LUC on water resources. A large majority rely on publicly available data sets (e.g., climate series, land-use maps, soil maps) or references from the literature and or other databases (e.g., life-cycle inventories) (Fig. 5.13b). Some studies are also based on expert opinion or on surveys.



(a) Methods used

(b) Data employed

**Fig. 5.13** Methods (**a**) and type of data (**b**) used to evaluate impacts on water resources

### 5.5.2 *Types of Impacts on Water Resources*

The impacts on water resources examined in these articles can be divided into two main categories: qualitative impacts or water pollution (eutrophication, biological or chemical pollution); and quantitative impacts, or water consumption. Within the 54 articles reviewed here, "water consumption" and "eutrophication" were the most commonly studied impacts (these two criteria corresponding to more than 65% of the scenarios assessed) (Fig. 5.14). Forms of water contamination other than eutrophication, whether chemical (e.g., introduction of trace elements or organic micro pollutants) or biological, were less frequently considered. (Note that a single article may consider several types of impacts.)

Water consumption (the "water footprint") corresponds to the quantity of water necessary for the production of a given quantity of biomass. There are several methods for calculating this, however: the "water footprint" may simply include surface or subsurface water used to produce the crop ("blue water"); or it may also include stored water in the soil lost through evapotranspiration by the crops ("green water"). In addition, it may take a qualitative view by considering the volume of water necessary to dilute any contaminants ("gray water"). However, none of these approaches specifically consider the environment in which the crop is located or from which the water is drawn. They thus estimate not so much an impact as simply the amount of water consumed. For this reason, some authors have proposed weighting water consumption according to a stress level (or "scarcity index"), and in this way accounting for the aridity of the specific environment (Nuñez et al. 2010; Motoshita et al.

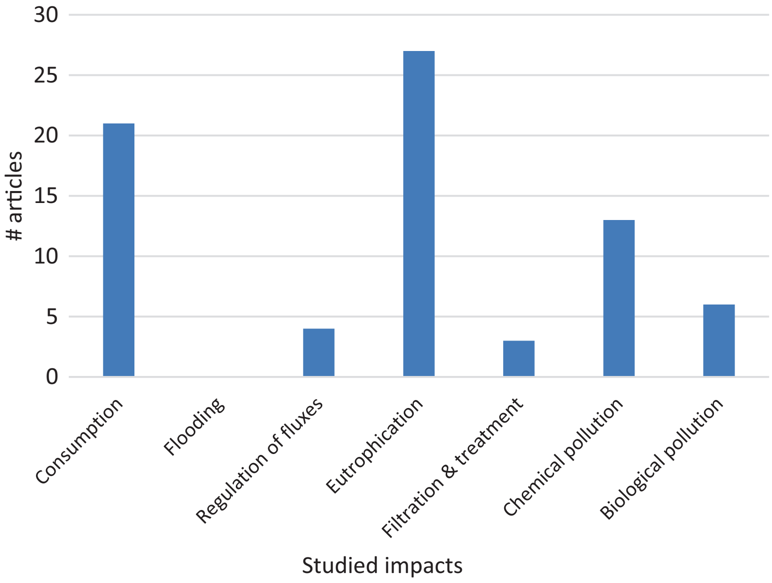


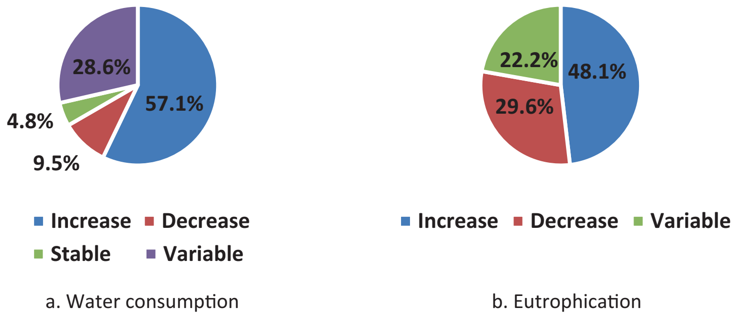
**Fig. 5.14** Impact criteria considered in the 54 articles

2014; Berger et al. 2014). In response to the heterogeneity of these different methods, in 2014, ISO Norm 14,046, "Water Footprint," was proposed as a way of harmonizing definitions and arriving at a standardized approach (ISO 2014).

The "water footprint" is generally expressed as a volume of water (e.g., L or $m^3$) per metric ton of biomass or per quantity of energy (in joules) produced. At a minimum, it includes atmospheric water (rain) and irrigation water (surface or subsurface). The amount of water needed for agricultural production varies widely depending on the geographic region and the crop being grown (Gerbens-Leenes et al. 2009a, b): the water footprint of corn, for example, varies from 153 to 3363 $m^3$/t (not including "gray water") depending on the country of production (e.g., the Netherlands or Zimbabwe); within a single country, the water footprint can vary from 150 $m^3$/t to over 450 $m^3$/t depending on the crop (e.g., wheat vs. rapeseed).

Among the articles in our sub-corpus looking specifically at the criterion of "water consumption" (21 articles out of the 54), 57%, or 12 articles, concluded there would be an increase in water usage resulting from non-food biomass production (Fig. 5.15a). Among these 12 articles, in 7 cases the increase in water consumption was associated with crops used for the production of first-generation biofuels, whereas crops used for second-generation biofuels increased water consumption in just 3 cases (in the 2 other cases, increased water consumption was associated with crops used for heat or for material products). Furthermore, in cases where water consumption decreased (2 articles), it was in association with crops for second-generation biofuels. Independent of the crops' final use, direct LUC (e.g., conversion of a forest or a grassland into crops for energy production) led to increases in water consumption in more than half of the studies.

The impact criterion of eutrophication corresponds to the modification and usually the degradation of aquatic environments resulting from excess nutrients, especially nitrogen and phosphorous. In cultivated systems, these nutrients are applied in the form of mineral or organic fertilizers, which if not fully utilized by crops can move into waterways, leading to imbalances in aquatic ecosystems (e.g., algal blooms, loss of biodiversity). In articles where the "eutrophication" criterion is studied (27 articles out of 54), more than 48%, or 13 articles, conclude there will be



a. Water consumption

b. Eutrophication

**Fig. 5.15** Modification of the impact criteria "water consumption" (21 articles) and "eutrophication" (27 articles) associated with changes in land use an increase in eutrophication (Fig. 5.15b). Among these articles, crops used for first-generation biofuel production contribute to this increase in 7 out of the 13 instances, whereas crops used for second-generation biofuels are responsible for only 2 instances (in the other 4 articles, increases in eutrophication are associated with the production of heat or biomaterials). In the case of direct LUC, associations are less clear than they are for water consumption. Thus, for example, replacement of an annual crop by a perennial crop (e.g., miscanthus, afforestation) reduces eutrophication in 5 out of 8 instances, whereas conversion of grasslands results in an increase in eutrophication in 6 out of 9 cases.

It is difficult to draw definitive conclusions with respect to the "consumption" and "eutrophication" criteria, however, since so many situations are considered "variable" (from 20% to 30% depending on the criterion). This is understandable given that impacts on water use depend on both the crop species and the climate scenario, as well as on the converted ecosystem (an irrigated annual crop replacing a grassland, for example, will generally consume more water). Eutrophication impacts likewise depend on fertilizer inputs and thus on the specific crop in question. Where eutrophication impacts decrease, in 7 situations out of 8 it is in association with perennial crops, as measurements and simulations reported in several articles confirm. Costello et al. (2009), Ng et al. (2010), Wu et al. (2012), and Sarkar and Miller (2014) all show that introducing perennial crops such as switchgrass and miscanthus can reduce fertilizer inputs (N and P) and soil erosion, and thereby reduce eutrophication of aquatic environments.

It is also difficult to draw generalizable conclusions because of the diversity of methodologies employed prior to 2014. Comparing "water footprints" prior to the establishment of ISO norm 14,046 is a challenge, generating controversy among scientists with regard to the very notion of a "water footprint" (Pfister et al. 2017). Finally, the perimeters established by different articles can also vary, with some seeking to measure the impacts of land-use change on water resources while others seek to compare the use of biomass materials compared to the use of fossil fuels. In the latter case, water consumption and eutrophication involved in the production of the energy crop is necessarily higher than for fossil fuels. Conversely, if one is interested in land-use change, pressure on water resources will vary depending on the crops established (e.g., perennials, annuals, irrigated or rainfed) and the type of ecosystem transformed. These two approaches are confounded within the database.

## 5.6 Conclusions

The impacts on water resources of land-use change associated with non-food crop production began to receive attention from researchers at the end of the 2000s. Both perennial crops (e.g. eucalyptus, willow, poplar, miscanthus, switchgrass, sugarcane, oil palm) and annual crops (e.g. corn, soybeans, rapeseed, sugar beet) are examined in the sub-corpus of 54 articles reviewed here. The use of whole plants or grain crops to produce first- or second-generation biofuels are the most frequently studied scenarios (more than 50% of articles), despite the fact that second-generation biofuels are still in development and even first-generation biofuels are less widespread than other forms of bioenergy (heat or electricity). The geographic regions considered with respect to these reorganizations are primarily South America and the USA (more than 50% of studies), followed by several European countries.

Within research on direct LUC, the most frequently transformed land-use categories are (in descending order) grasslands, arable crops, and forests. Land-use conversion usually results in the establishment of perennial or annual crops. Afforestation is also sometimes involved, but this is less common. In the case of indirect LUC, conversions likewise usually result in the establishment of perennial or annual crops, but the transformed environments are different, with forests most often affected, then grasslands, then arable crops. The geographic regions receiving the most attention are in the Americas, especially South American countries (Brazil, Argentina); or a global focus is adopted.

Assessments of the impacts of land-use change on water resources are made using a variety of approaches, generally prospective in nature. Studies based on empirical data are rare (less than 5%), even when the level of spatial analysis is the field, planting, or region. The studies surveyed here primarily make use of life-cycle analysis (LCA) or biophysical models (alone or in tandem) as their methodology. The most frequently considered impacts are water consumption and the eutrophication of aquatic environments. Although it is not possible to draw a definitive conclusion given the diversity of situations examined and methods employed, it would appear that crops used for the production of second-generation biofuels are less consumptive of water and less damaging for aquatic environments.

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## Annex: References in the Study Corpus Addressing Impacts on Water

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# Chapter 6
# Review of the Impacts on Greenhouse Gas Emissions of Land-Use Changes Induced by Non-food Biomass Production

**Laure Bamière and Valentin Bellassen**

**Abstract** The recent development of biomass production for energy purposes has spurred interest in the effects of the land-use changes (LUC) it triggers worldwide, and a surge in the number of scientific articles dealing with this topic. The processes leading from increased biomass demand to environmental impacts in relation to LUC may be analyzed as a three-step causal chain starting with the identification of reorganization of agricultural and forestry systems, the assessment of LUC occurring in response to these drivers, and the associated environmental impacts. Here we set out to review the impacts of land-use changes induced by non-food biomass production on greenhouse gases emissions. The selected body of 162 articles displays the following salient features: most articles deal with LUC triggered by biofuel production, the predominant direct LUCs are forest or grassland conversions into annual or perennial crops, and annual crops conversion into perennial crops; and while Europe and North America come first in terms of direct LUC location, a large number of articles also deal with direct LUCs occurring in South America and Asia. We show that peer-reviewed literature does not sign a blank check to non-food biomass. The number of articles evidencing a net reduction in GHG emissions following a diversion of food/feed crops towards non-food products is only 50% higher than the number of articles drawing opposite conclusions. As the LUC-related carbon intensity of biofuels strongly depends on where the feedstock is grown and which land-use it replaces, we investigated whether specific land-use change patterns can be tied to certain types of feedstocks. Contrary to our expectations, direct forest and grassland conversion is significantly less often considered for second generation feedstocks or wood.

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**Keywords** Biofuels · Bioenergy · Biomass · Land-use change · Climate · Greenhouse gas · Impact · Forest · Grassland · Cropland · Location

## 6.1 Introduction

Biomass production has developed significantly in the latest decade to meet the needs of the bioeconomy (bioenergy, biomaterials etc…), and this trend is expected to continue in the near future to substitute dwindling fossil resources (Chum et al. 2011). Concerns were recently raised around the consequences on land-use and land-use changes (LUC) incurred when expanding feedstock production (Searchinger et al. 2008). These concerns prompted a surge in scientific publications over the past 10 years (Réchauchère et al. General Introduction, this volume), together with debates and revisions in public policies supporting the use of biofuels. Attributing LUC to biomass production and ultimately the rising demand for end-products (e.g. biofuels) requires the elicitation of mechanisms relating feedstock production to land use or management changes, and their impacts on the environment. They may be analysed as a three-step causal chain: shift from food to feedstock production, LUC occurring in response to this shift – whether direct or indirect, and impact assessment along various dimensions, such as greenhouse gas (GHG) emissions, biodiversity, water resources, soil quality, or atmospheric pollution.

Pieces of work were recently published reviewing this emerging and dynamic research area (Berndes et al. 2013; Broch et al. 2013; Djomo and Ceulemans 2012). These reviews narrow down a list of key drivers for the carbon intensity of biofuels, and offer some insights on how they play out. They are not conclusive however on whether biofuels have a lower carbon intensity than fossil fuels in general.

One reason for this inability to conclude may be the small number of studies considered. Indeed, none of them involved a systematic survey of literature encompassing the full causal chain between non-food biomass expansion, its drivers, and environmental impacts. A recent review of such approaches, often used as a basis for meta-analyses, concurred in highlighting this gap in the context of "land-use science" (van Vliet et al. 2016), revealing a decoupling between drivers of LUC and their impacts. Moreover, these recent reviews are highly selective, either focusing on the differences in the indirect land-use change (iLUC) impact of biofuels or applying stringent quality criteria during study selection. Broch et al. (2013) considers 6 studies and Djomo and Ceulemans (2012) reviews 15 peer-reviewed articles.

Here, we set out to review the impact of non-food biomass diversion on GHG emissions and carbon sequestration – hereafter referred to as GHG emissions – in the peer-reviewed literature. We also aim at providing insights on the drivers of these impacts and their variability. Our study complements the aforementioned reviews in two ways: (a) we systematically capture all peer-reviewed articles which cover the full causal chain from non-food biomass diversion – including other non-food uses than biofuels – of land to climate mitigation impact and (b) we apply no other quality criteria and therefore retain a large bod totalling 162 articles. Unfortunately, this larger number of articles does not provide a much more conclusive answer to the question. It does however provide a ratio: the number of studies finding a net reduction in GHG emissions for non-food biomass diversions is 50% higher than the number of studies with the reverse conclusion.

As demonstrated initially by Fargione et al. (2008) and later confirmed by many modeling studies including recently Elshout et al. (2015), the LUC-related carbon intensity of biofuels much depends on where the biofuel feedstock is grown and which land-use it replaces. One avenue for finding non-food biomass diversions which reduce GHG emissions is therefore to track the nature and location of the associated land-use changes. In particular, feedstocks for second generation biofuels and wood-based energy have been promoted as better suited to replace marginal lands than first generation biofuels feedstocks. The last part of this article investigates whether specific land-use change patterns can be tied to certain types of feedstocks.

In the following section, we explain the selection criteria for the articles, together with the nature of extracted information. In a third section, we provide descriptive statistics on this selected body of literature. The fourth section is dedicated to quantitative findings on the impact of non-food biomass diversions on GHG emissions and the fifth section investigates the links between land-use change patterns and feedstock types.

## 6.2 Materials and Methods

### *6.2.1 Literature Survey, Definition and Analysis of a Relevant Set of References*

In a first step, we surveyed the scientific literature on LUC in general between 1975 and February 2015, and retrieved a body of 5730 articles from 2 data bases relevant to this topic (Web of Science and CAB, see Rechauchère et al., Chap. 1, this volume). All references included keywords related to land-use changes, but another constraint was that references should cover the 3 steps of the drivers to impacts causal chain, i.e. including a mention to a particular end-product (or several of them), a type of biomass feedstock, and at least one category of environmental impacts among the following: climate (including GHG emissions), consumption of non-renewable resources, biodiversity, water resources, soil quality, atmospheric pollution, human health, and ecotoxicity.

An automated textual analysis of the papers' abstracts, title and keywords evidenced a series of themes structuring this set of references (El Akkari et al. Chap. 2, this volume), and the subset on the impacts of biomass/bioenergy through LUC effects was selected. This set of 1785 articles was further screened manually by a dozen of experts in the fields covered by this literature (economics, ecology, agronomy, forestry, and sustainability assessment), and winnowed down to 241 references (Rechauchère et al., Chap. 1, this volume). These were further analysed in details in terms of scope, LUC types,[1] methodologies employed, and overall impacts of biomass production.

### 6.2.2 Statistical Models

Many articles do not provide figures on GHG emissions that can be easily extracted and compared to one another. In order to retain as many articles as possible, we therefore restrict our analysis to whether the shift towards non-food biomass results in a net increase in GHG emissions.

The main drivers identified by Djomo and Ceulemans (2012) for the impact of a biofuel diversion on GHG emissions are: the type of land-use converted, its carbon stock, crop yield, whether crop residues or co-products are used and the price-elasticity of the re-directed crop.

In an attempt to identify the key drivers of climate mitigation impact, the following list of possible drivers is established:

- whether the studies estimates iLUC,
- whether LUC from forest occur,
- whether LUC from grassland occur,
- whether one of the crops studied can be used as feedstock for first generation biofuel, second generation biofuel – excluding trees – or whether a tree species is among the crops studied,
- whether one of the crops studied can be used as feedstock for ethanol or diesel.

In addition, the impact of methods is tested by including a dummy variable indicating whether a specific method – life-cycle analysis, economic model, biophysical model, process-based model or basic calculation – is used in the article. A stepwise Akaike Information Criterion (AIC) model selection procedure is applied to probit models explaining the probability that a study finds a decrease in GHG emissions on the subsample of studies finding a clear result (either an increase or a decrease in emissions).

Similarly, a probit model is used to assess whether feedstocks for second-generation biofuels or wood are more associated with forest or grassland conversion than first generation biofuels feedstocks.

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[1] We distinguish two types of land use changes: direct and indirect. Direct LUC (dLUC) refers to situations where the expansion of a crop leads to a change in land use category (e.g. grassland converted to corn production). Indirect LUC (iLUC) describes a situation where a change in cropping practice or crop production end-use at a given place (e.g. a biofuel crop replaces a food crop) leads to a change in land use category at another place (e.g. forest land is converted to cropland for food production). Here we use the land use categories defined by IPCC 2006 (i.e., forest land, cropland, grassland, wetlands, settlements), to which we added a “perennial crop” category which is normally included in cropland.

## 6.3 Descriptive Statistics of the Set of References

162 articles assess the climate impact of a land-use change induced by the production of non-food biomass. This sub-sample adds up to 69% of all articles assessing an environmental impact of non-food biomass diversion as selected by Réchauchère et al. (Chap. 1, this volume). Unsurprisingly, most of its descriptive statistics are therefore similar to those of the overall selection (Gabrielle et al., Chap. 3, this volume). The database constituted from the 162 articles assessing the climate mitigation impact of non-food biomass production shifts, including the reference of each article and many other pieces of information extracted from them, is provided as a supplementary material to this article.

### *6.3.1 Drivers of Land-Use Changes*

#### 6.3.1.1 The Study of Impacts on Climate Began in 2008

Impacts of land-use change on climate started being studied in 2008 (see annex, Fig. 6.15). In their literature review on the carbon impact of biofuels, Djomo and Ceulemans (2012) pinpointed the same year as a turning point. The fact that a few articles in our sample were published prior to 2008 can be explained by a difference in the selection criteria, which were stricter in the Djomo and Ceulemans (2012) review. For instance, they introduced a criterion on the quality of the methodology.

#### 6.3.1.2 Biomass Feedstock Types and End-Uses

The types of feedstock species most frequently studied are wood, corn, miscanthus, soybeans, sugar cane, switchgrass, oil palm, rapeseed and wheat (see annex, Fig. 6.16). Here we find unsurprisingly species for the production of first generation biofuels (cereals, oilseeds, sugar cane, see Fig. 6.1), and lignocellulosic biomass (e.g. herbaceous species, wood in Fig. 6.1) which has different end uses (e.g. second biofuel generation, power, heat, …). The “wood” category is mainly composed of poplar, willow, and eucalyptus short rotation coppices, but also of hardwood and softwood.

Biomass feedstock is mainly used for the production of 1st and 2nd generation biofuels (58% of the occurrences, see Fig. 6.2), but also of power, heat and methane (16%, 8%, and 4% of occurrences respectively). Non-energy uses are a minority and represent only 8% of cases.

Non-food biomass diversion is predominantly driven by public policies: 69%, of the 62% of the articles where the drivers of the diversions are identified mention public policies. European and American policies are most represented, with 30% of cases each. Then come Latin American countries, such as Brazil and Mexico, with

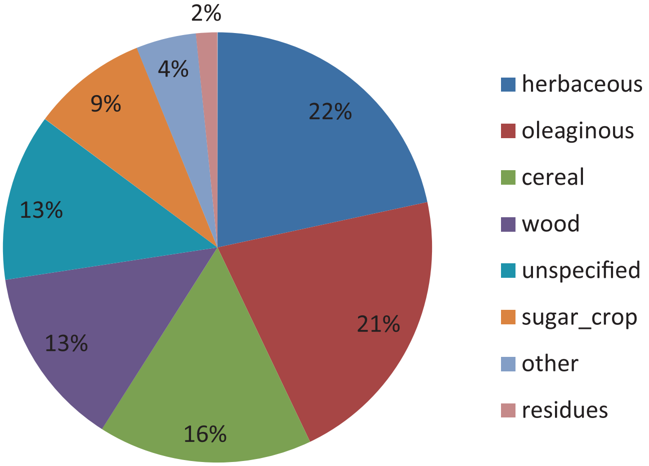


**Fig. 6.1** Broad categories of feedstocks studied in the articles. Results are expressed in % of 310 occurrences (a single article can study several end-uses)

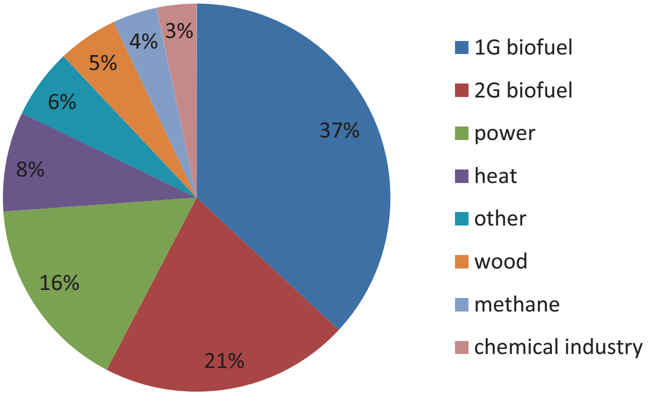


**Fig. 6.2** End uses of non-food biomass. Results are expressed in % of 241 occurrences (a single article can study several end-uses)

10% of cases and Southeast Asia with 7%. Finally, in 11% of cases, non-food biomass production is driven by a set of energy policies throughout the world. These results are consistent with the geographical distribution of non-food biomass shifts.

The European policies driving the land-use changes are predominantly the EU directives on Renewable Energy Sources (2009-28-CE, 14%) and on liquid biofuels (2009/30/CE, 11%) as well as the European carbon market (4%). The US policies are mainly the 2005 Energy Policy Act (18%), the Renewable Fuel Standards 2 (RFS2), Renewable Portfolio Standards (RPS), and Renewable Electricity Standards (RES) policies (11% for all three combined). Again, this is consistent with the types of biomass feedstocks and end-uses reported.

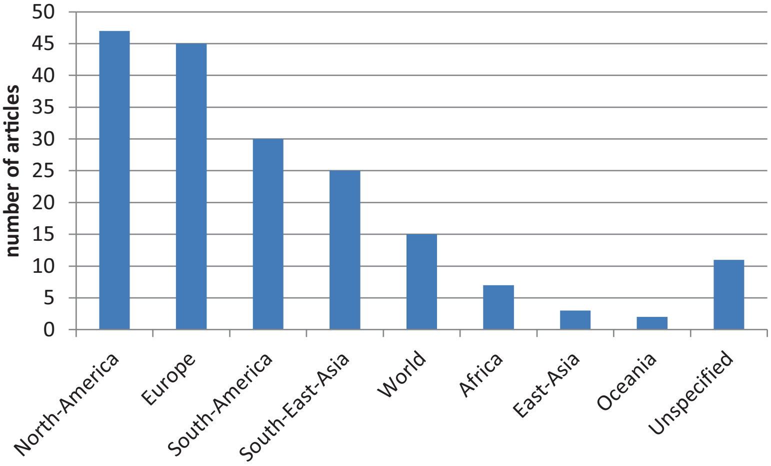


**Fig. 6.3** Distribution of articles among geographical locations of shifts towards non-food biomass production, by major world regions

#### 6.3.1.3 Non-food Biomass Diversions Often Take Place in Developing Countries

Although the most frequently studied continents in terms of non-food biomass are North America and Europe, a fair amount of articles assess the climate impact of production shifts taking place in South America and Southeast Asia (Fig. 6.3).

85% of the diversions studied take place at large scales (region or larger), with a majority referred to national scale or below (see annex, Fig. 6.17). This is consistent with the paucity of primary data used in these studies to assess the climate mitigation impact (Sect. 3.3.2): primary data and plot-scale often go hand in hand.

Figure 6.4 shows the spatial resolution that is adopted depending on the scale of the shift. Very often the spatial resolution is not specified (34% of articles), or is identical to the scale (33% of articles). The latter case is almost systematic for small scales (plantation and below) and the continental scale. In the remaining articles, the most common spatial resolution is the plot, followed by the region, the transect and the continent.

### *6.3.2 Land-Use Changes*

#### 6.3.2.1 Forest and Grassland Conversions Dominate

The most studied land-use changes are forest and grassland conversions into cropland (Table 6.1 and Table 6.2). The indirect land-use change matrix is less asymmetrical than the direct land-use change matrix: grassland to cropland conversions are 7 times more frequent than cropland to grassland conversions in the direct matrix

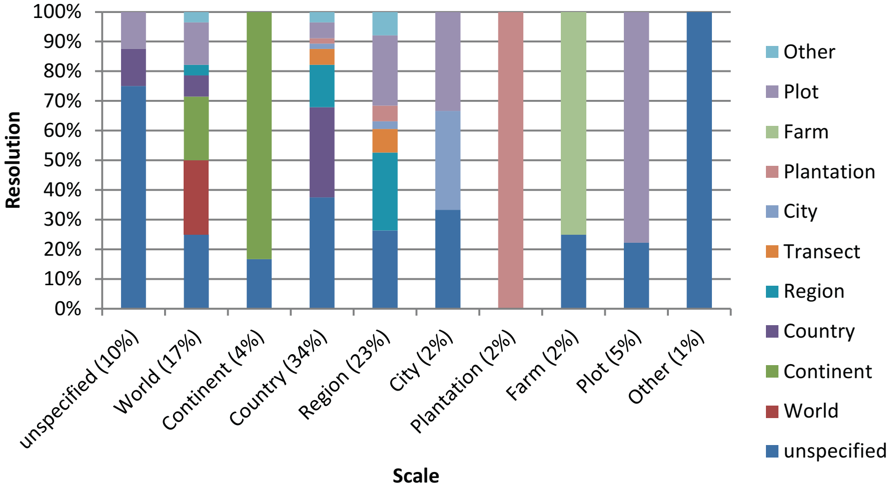
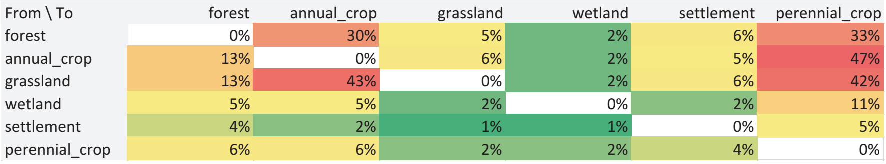


**Fig. 6.4** Links between the spatial resolution and the scale at which shifts are studied. For instance, 14% of articles studying a shift in a country do it with a region spatial resolution, while 30% remain at the country level

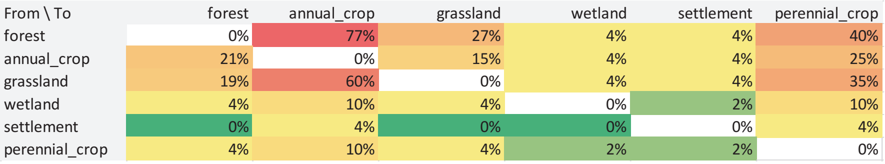
**Table 6.1** Direct land-use change matrix



| From \ To | forest | annual_crop | grassland | wetland | settlement | perennial_crop |
|---|---|---|---|---|---|---|
| forest | 0% | 30% | 5% | 2% | 6% | 33% |
| annual_crop | 13% | 0% | 6% | 2% | 5% | 47% |
| grassland | 13% | 43% | 0% | 2% | 6% | 42% |
| wetland | 5% | 5% | 2% | 0% | 2% | 11% |
| settlement | 4% | 2% | 1% | 1% | 0% | 5% |
| perennial_crop | 6% | 6% | 2% | 2% | 4% | 0% |

Percentages indicate the proportion of articles which study the type of direct land-use change among the 126 articles with at least one direct land-use change

**Table 6.2** Indirect land-use change matrix



| From \ To | forest | annual_crop | grassland | wetland | settlement | perennial_crop |
|---|---|---|---|---|---|---|
| forest | 0% | 77% | 27% | 4% | 4% | 40% |
| annual_crop | 21% | 0% | 15% | 4% | 4% | 25% |
| grassland | 19% | 60% | 0% | 4% | 4% | 35% |
| wetland | 4% | 10% | 4% | 0% | 2% | 10% |
| settlement | 0% | 4% | 0% | 0% | 0% | 4% |
| perennial_crop | 4% | 10% | 4% | 2% | 2% | 0% |

Percentages indicate the proportion of articles which study the type of indirect land-use change among the 48 articles with at least one indirect land-use change

and only 4 times more frequent in the indirect matrix. This difference in asymmetry likely comes from the economic models used to assess indirect land-use changes. Indeed, following a biomass diversion, these models tend to simulate all the types of land-use changes although not in the same proportion of course (see Sect. 4.2.1).

One can also notice two other differences between direct and indirect land-use changes: the main origin of direct land-use change is grassland whereas it is forest for indirect land-use change. On the destination side, annual crops clearly dominate the indirect matrix while perennial crops is also a common destination for direct land-use changes.

Half of the articles contain both *ex ante* – that is prospective – and *ex post* – that is retrospective – assessments of the climate impact of non-food biomass diversions. 40% of the articles however focus on *ex ante* assessments.

## *6.3.3 Impacts on GHG Emissions*

### 6.3.3.1 The Impact on Climate Is Often Studied Alone

The impacts on water, soil (other than carbon) and fossil resources depletion and waste are the three impact categories most often assessed jointly with climate mitigation with around 20% each (Fig. 6.5). Studies with all three categories assessed in addition to climate mitigation – likely life-cycle assessment – only represent 7% of all studies which assess the climate mitigation impact.

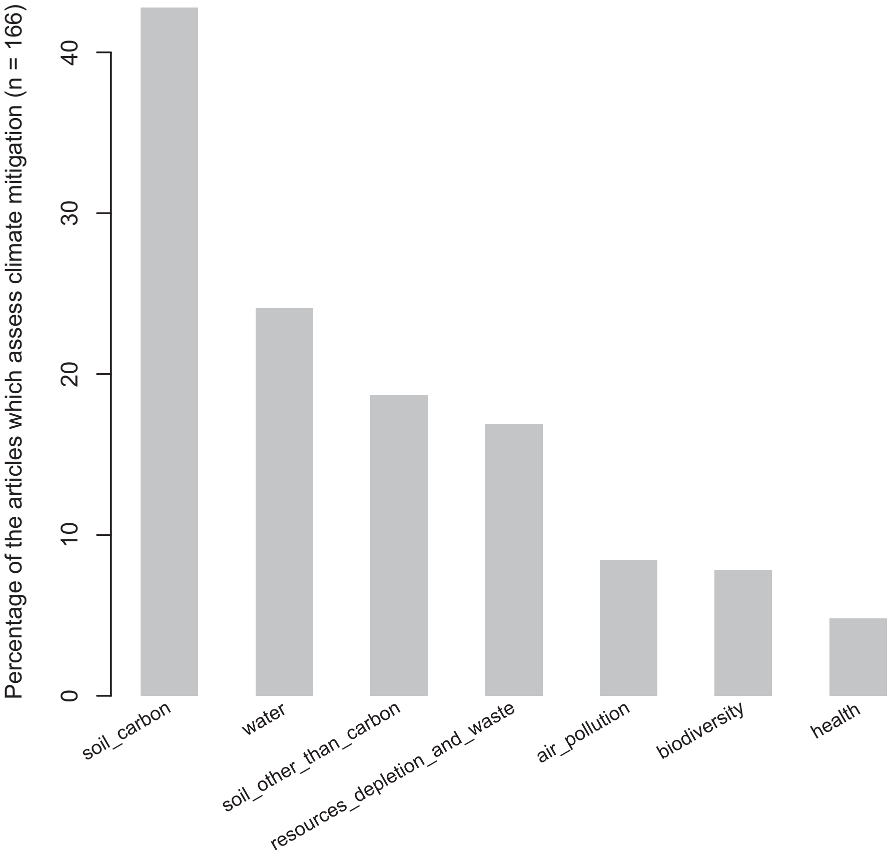


**Fig. 6.5** Environmental impacts assessed jointly with climate mitigation

#### 6.3.3.2 Three Fourth of the Articles Do Not Collect Original Data to Assess the Climate Mitigation Impact

Only 27% of all articles use measurements to assess the impact of land-use change on climate. 66% of these are assessing soil carbon changes. Hence, most of the articles which cover the entire causal chain "*diversion/land-use change/climate mitigation impact*" are not field studies: they use secondary data and model outputs to quantify GHG emissions or sequestration following land-use changes. Conversely, reference meta-analysis or analysis of the climate mitigation impact of land-use changes (Baccini et al. 2012; Harris et al. 2015; Kim and Kirschbaum 2015; Poeplau et al. 2011; Poeplau and Don 2013; Saatchi et al. 2011) are not retained in our sample. Indeed, these articles focus on the climate mitigation impact of land-use changes and do not mention the drivers of these changes. Note that we focus here on the data used to assess the environmental impact. The other 73% of articles are therefore not necessarily "pure" modeling studies: some of them are collecting primary data to assess diversions or land-use changes.

#### 6.3.3.3 Life-Cycle Analysis Is the Most Often Used Method

More than half of the articles use life-cycle assessment (Fig. 6.6). Logically, this method is mostly used for the assessment of climate mitigation impact rather than for the assessment of biomass production shifts and land-use changes (see Appendix 7.1). Biophysical and economic models are used by 20% of the articles and are jointly used in almost 10% of cases. Only 20% of the articles do not use any of these three most popular methods.

## 6.4 Results and Discussion

### *6.4.1 The Climate Mitigation Impact of Non-food Biomass Is Not Overwhelmingly Positive*

Peer-reviewed literature does not sign a blank check to non-food biomass. The number of articles finding a decrease in GHG emissions or an increase in carbon sequestration following a diversion of food/feed crops towards non-food products is only 50% higher than the number of articles with opposite conclusions (Fig. 6.7[2]). In their review restricted to first generation biofuels, Djomo et Ceulemans (2012) come to the same ambivalent conclusion. Such conclusions weaken the climate mitigation rationale frequently used to support policies in favour of non-food bio-

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[2] The full list of references and their classification as regards mitigation impact is available online as supplementary material.

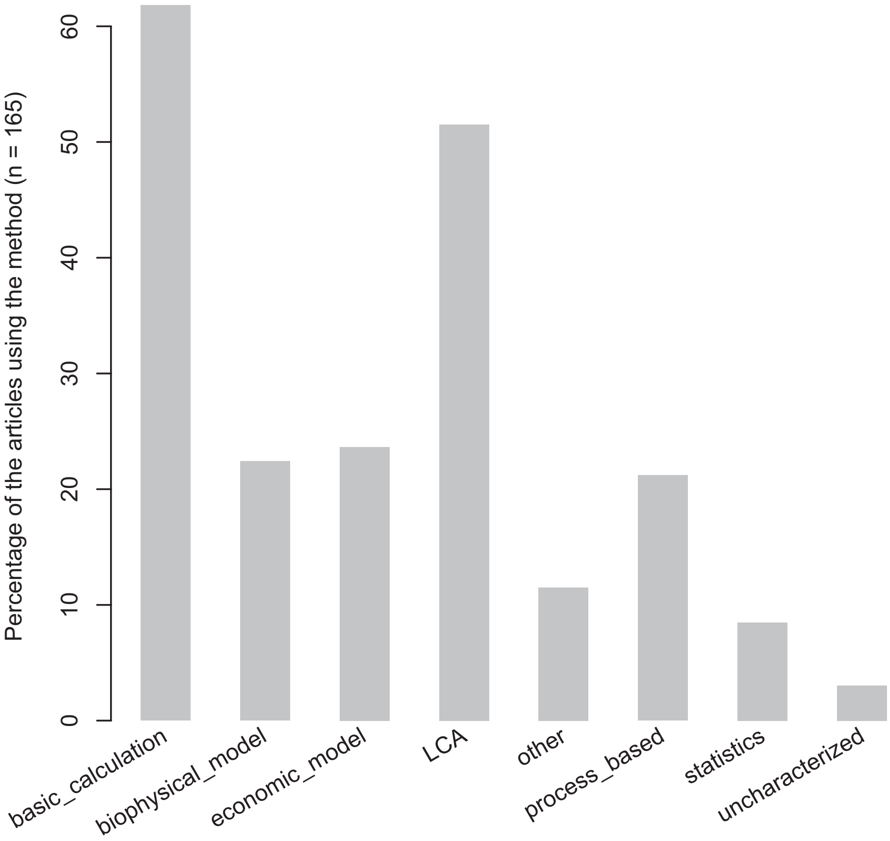

**Fig. 6.6** Methods used to assess part of the chain "diversion/land-use change/climate mitigation impact". *A single article can use several methods, hence the sum of percentages is higher than 100*

mass. El Akkari et al. (2018) however, find a more systematically favourable outcome for biofuels.

The stepwise AIC model selection procedure retains two possible drivers with a significant impact. The probability to find a decrease in GHG emissions is significantly lower – by 21 percentage points – in articles with a least one crop which can be used as feedstock for second generation biofuel (Table 6.3). This somewhat counter-intuitive finding could be related to the lower occurrence of grassland or forest conversions in articles assessing 2G biofuel feedstocks. The probability to find a decrease in GHG emissions is also 37 percentage points lower in articles using an economic model.

The probability to find a decrease in GHG emissions is also 17 percentage points higher in articles with at least one biodiesel 1G feedstock although this results is only marginally significant (p-value = 0.08). To the contrary, this probability is lower and non-significantly different from zero in articles with at least one bioethanol 1G feedstock. Because 2G feedstock can usually be turned into either bioetha-

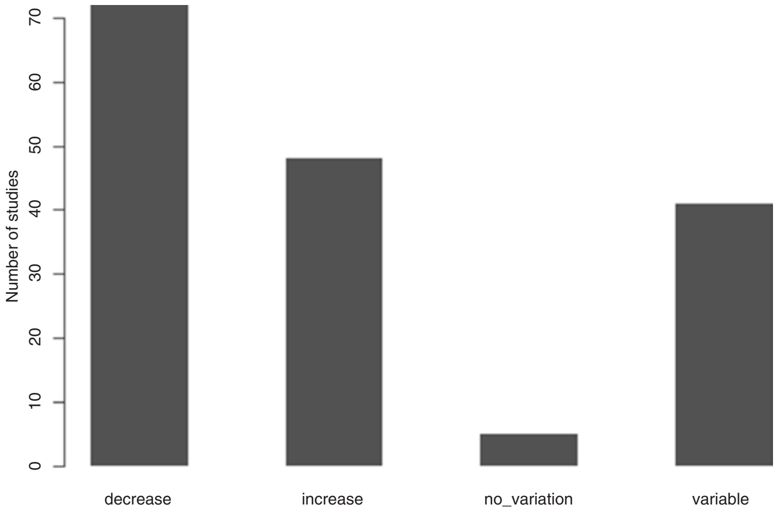

**Fig. 6.7** Climate mitigation impact of non-food biomass (decrease stands for decrease in GHG emissions or increase in carbon sequestration)

**Table 6.3** Marginal effect of 2G feedstock and the use of economic models on the probability that the outcome is a decrease in GHG emissions

| | Marginal effect ± 95% CI |
|---|---|
| Feedstock for 2G biofuel | -0.21 ± 0.18 |
| Economic model used | -0.37 ± 0.69 |

nol and/or biodiesel, this result is obtained on the sole basis of 1G feedstocks. Moreover, it is entirely due to the correlation with the type of method used: when methods – or even only the use of economic models – are controlled for, the advantage of biodiesel studies disappears. The absence of difference between the two feedstocks (1G and 2G) is consistent with El Akkari et al. (2018), but somewhat contradictory to Djomo et Ceulemans (2012) which finds that the carbon debt of biodiesel tends to be higher than that of bioethanol. Both findings are clearly fragile. In both cases, methods and assumptions of each article can largely drive the results beyond the elements that can be controlled for such as whether iLUC is estimated. Compared to Djomo et Ceulemans (2012), our result has one additional strength and two additional weakness. Our strength comes from the much higher number of articles considered – 120 vs 15. Our weaknesses lie in the binary nature of the outcome we consider – whereas Djomo et Ceulemans (2012) look at the more precise carbon intensity in g $CO_2$ $MJ^{-1}$ – and in the significant proportion of articles which study both ethanol and diesel feedstocks. One third of the 40 articles studying diesel feedstock also study ethanol feedstock.

An important limit in this attempt to identify the drivers of the climate mitigation outcome is the lack of information on the way co-products are handled. Indeed, in

**Table 6.4** Average characteristics of articles per category of GHG impact

| | Impact on GHG emissions | | | | |
|---|---|---|---|---|---|
| | decrease | increase | no_variation | variable | all |
| Presence of iLUC | 31% | 34% | 0% | 24% | 29% |
| Presence of both 1G and 2G feedstock | 13% | 17% | 0% | 12% | 13% |
| Presence of both ethanol and diesel feedstock | 13% | 9% | 20% | 7% | 10% |
| Methods include basic calculations | 36% | 36% | 40% | 32% | 35% |
| Methods include a biophysical model | 18% | 17% | 0% | 12% | 16% |
| Methods include an economic model | 4% | 17% | 0% | 5% | 8% |
| Methods include a LCA | 47% | 43% | 100% | 61% | 51% |
| Methods include a process-based model | 78% | 15% | 0% | 12% | 12% |
| Number of scenari* | 3.36 | 4.53 | 1.80 | 3.98 | 3.80 |
| Number of species | 3.02 | 3.31 | 2.60 | 3.00 | 3.07 |

E.g. 31% of the articles which find a decrease in GHG emissions estimate an iLUC effect against 29% for all the articles. * The number of scenarios is artificially capped at 10 scenarios per article. 'Variable' means that within one article, the various scenarios explored lead to different conclusions in terms of GHG emissions

the case of biofuels, Taheripour et al. (2010) finds that ignoring the use of co-products leads to an average overestimation of land-use changes by 27%. Similarly, Elshout et al. (2015) finds that failing to attribute part of the LUC-related carbon footprint to co-products leads to a 43% (market value allocation) to 300% (mass allocation) overestimation of the carbon payback time of biofuels. Therefore, future reviews and meta-analysis on this topic should gather data on whether co-products are accounted for and how the climate mitigation impact is allocated between products and co-products.

The second interesting result we obtain on the climate mitigation impact of non-food biomass reorientation is the large number of studies – one third – which find a *variable* impact. Many articles indeed study several scenarios or several species – 78% and 61% of all articles respectively – and find an increase in GHG emissions for some scenarios and a decrease in GHG emissions for others. What drives this variability is not obvious: a stepwise AIC model selection procedure applied to the possible drivers listed in Table 6.4 does not retain any of them.

## 6.4.2 *Relationships Between Species, Land-Use Change Type and Land-Use Change Location*

### 6.4.2.1 Direct Forest and Grassland Conversion Is Less Often Considered for Second Generation Feedstocks

Second generation (2G) biofuels are commonly supposed to be more sustainable than first generation (1G) ones (eg. Chum et al. 2011; Farrell 2006; Pimentel and Patzek 2005). One of the arguments in their favour is that they can be made from perennial crop feedstocks which are assumed to be able to grow more easily on

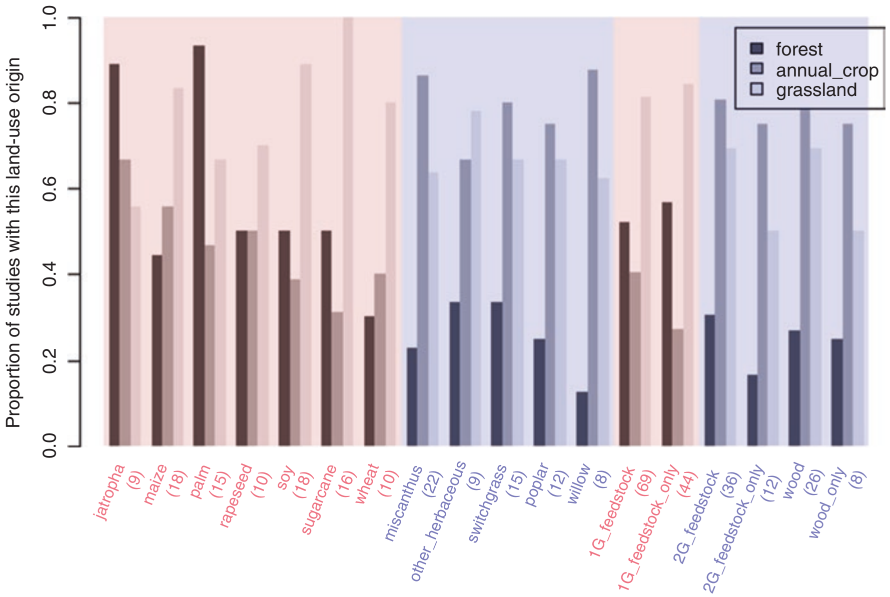

**Fig. 6.8** Origin (forest/annual crop/grassland) of direct land-use change per crop type
Crop types depicted in red are suitable feedstock for 1G biofuel. Crop types depicted in blue are suitable feedstock for second generation biofuels. The number of articles per crop type is in parenthesis. Only categories with a least 8 articles are displayed. According to our definition of land-use change (see Sect. 2.1), annual crops displacing annual crops are not counted. However, the results are somewhat blurred by articles which study different crops simultaneously. Categories "1G_feedstock_only", "2G_feedstock_only" and "wood_only" regroup articles which concentrate on crops from a single crop type (1G feedstock, 2G feedstock excluding wood and wood)

marginal lands than 1G feedstocks. One would therefore expect that their assessment focuses on perennial crops replacing forests or (eg. Gelfand et al. (2013). To the contrary, the articles which focus on 2G feedstocks or wood include significantly less often conversions of forests or grasslands (Fig. 6.8, Table 6.5).

Articles which focus on ethanol feedstock are significantly more often associated with conversions of grassland than articles focusing on diesel feedstock. This may explain why biodiesel more often has a positive climate mitigation impact than bioethanol in our sample. There is however no significant difference between ethanol and diesel feedstock regarding association with deforestation.

One notable crop-specific feature is that jatropha and palm are more often associated with deforestation than other crops (Fig. 6.8).

No specific association feature could be found between a given crop and a given origin of indirect land-use change (Fig. 6.9). The noise generated by articles which cover different crop types combined with the small sample size, especially for 2G feedstocks, partly explains this lack of crop specificity. Another explanation lies in the use of general equilibrium models to assess indirect land-use change. Indeed, these models often simulate all types of land-use changes following a shift to non-food biomass. The simulated amount of hectares concerned in each land-use change

**Table 6.5** Probit models of type of land-use as function of feedstock

| | *Dependent variable:* | |
|---|---|---|
| | dLUC_from_forest | dLUC_from_grassland |
| feedstock2G_only | −1.139$^{**}$ (0.471) | −0.998$^{**}$ (0.427) |
| wood_only | −0.846 (0.518) | −0.998$^{**}$ (0.498) |
| Constant | 0.172 (0.190) | 0.998$^{***}$ (0.227) |
| Observations | 64 | 64 |
| Log likelihood | −39.994 | −33.142 |
| Akaike Inf. Crit. | 85.987 | 72.284 |

*Note:* $^{*}p^{**}p^{***}p < 0.01$

The probit models are applied to the subset of articles which do not include several crop types, corresponding to "_only" categories in Fig. 6.8

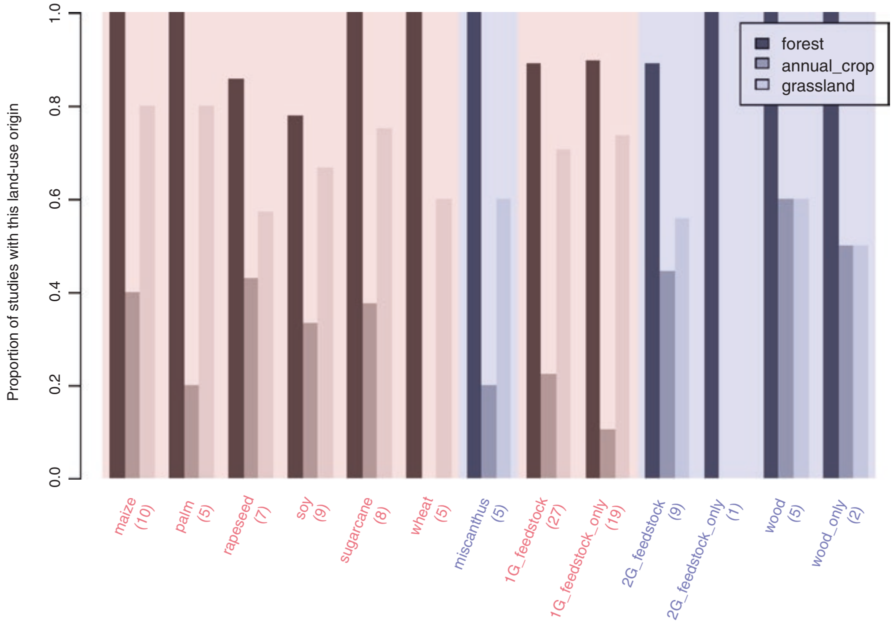

**Fig. 6.9** Origin (forest/annual crop/grassland) of indirect land-use change per crop type
Crop types depicted in red are suitable feedstock for 1G biofuel. Crop types depicted in blue are suitable feedstock for second generation biofuels. The number of articles per crop type is in parenthesis. Only categories with a least 5 articles are displayed. The results are somewhat blurred by articles which study different crops. Categories "1G_feedstock_only", "2G_feedstock_only" and "wood_only" regroup articles which concentrate on crops from a single crop type (1G feedstock, 2G feedstock excluding wood and wood)

category however may dramatically vary. Broch et al. (2013) for example finds an important differences in the share of forests and grasslands indirectly impacted by biofuel production: the share of forests in indirectly converted areas varies y from 22% to 67% and the share of grassland varies from 33% to 78%.

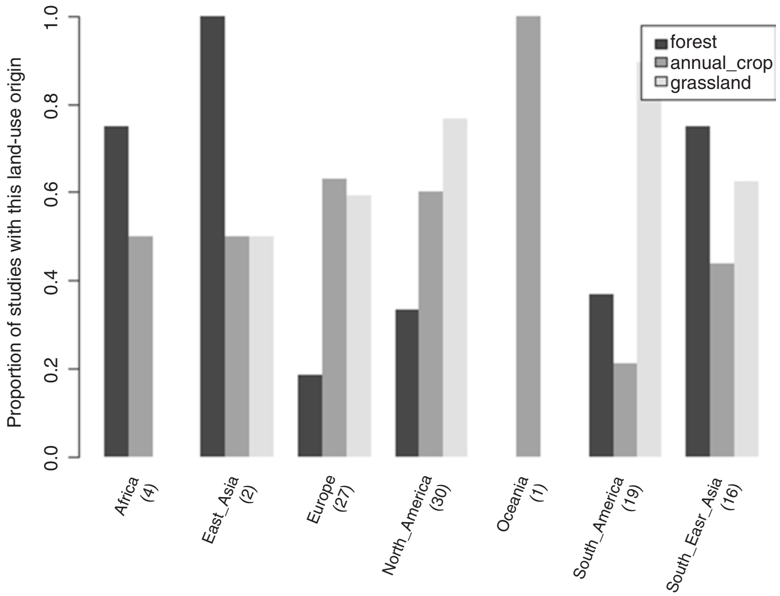

**Fig. 6.10** Origin (forest/annual crop/grassland) of direct land-use change per diversion location Only articles which focus on a single location are displayed. The number of articles in each location category is given in parenthesis

### 6.4.2.2 Land-Use Change Location

The location of biomass production shifts does not generate any clear difference in the origin (forest vs annual crop vs grassland) of direct (Fig. 6.10) or indirect (Fig. 6.11) land-use change. This is particularly true for the two most represented continents, namely Europe and North America. In South America, the share of articles with converted grassland is slightly higher than in other continents, reaching 85%, while in South East Asia, the share of articles with deforestation is notably higher than in other continents, reaching 75%. The latter figure is consistent with the fact that South East Asia is the continent where deforestation rates are the highest (FAO 2015). In both cases however, the small sample size forbids any clear-cut conclusion.

Most of the articles which report indirect land-use changes estimate it at a global scale (Fig. 6.12). Despite the small sample size, there is a clear distinction between industrialized and developing continents: when the biomass diversion occurs in Europe or in North America, the global scale is by far dominant. However, when the biomass diversion takes place in South America or South East Asia, the articles considering indirect land-use change only within the same continent are at least as numerous as the articles which take a global approach.

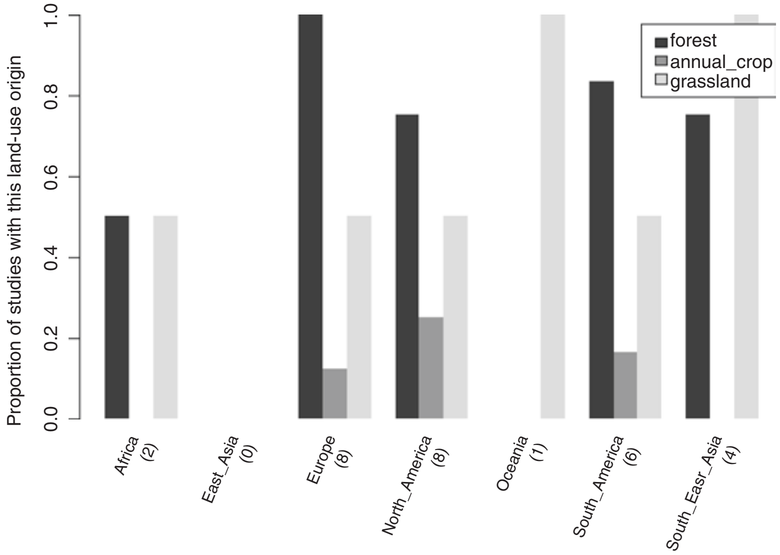

**Fig. 6.11** Origin (forest/annual crop/grassland) of indirect land-use change per diversion location

Only articles which focus on a single location are displayed. The number of articles in each location category is given in parenthesis

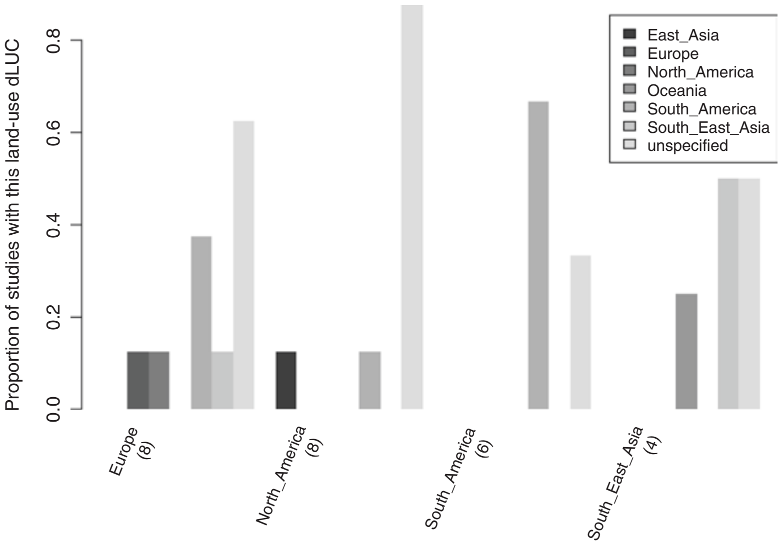

**Fig. 6.12** Location of indirect land-use change per diversion location

The diversion location is presented on the x-axis. The different shades of grey indicate the location of indirect land-use change. Only articles which focus on a single location are displayed. The number of articles in each location category is given in parenthesis

## 6.5 Conclusion

In this article we set out to review the impacts of land-use changes induced by non-food biomass production on GHG emissions. For that purpose, we systematically captured all peer-reviewed articles which cover the full causal chain from non-food biomass diversion of land to climate mitigation impact. We applied no other quality criteria and therefore retained a large body of 162 articles.

Liquid biofuels accounted for 58% of non-food biomass end-uses (37% and 21% for 1st and 2nd generation respectively), followed by combustion for power and heat production cumulating 24%. Non-energy uses such as biochemicals and biomaterials were a minority and only represented 8% of biomass end -uses.

The predominant direct land use changes are forest and grassland conversion into cropland, with similar rates for both annual and perennial crops, as well as the conversion of annual crops into perennial crops. These observations hold for indirect land-use changes except that forest is the main origin and annual crops are the main destination. In terms of methodologies, 73% of the articles do no collect original data to assess the climate mitigation impact: they use secondary data and model outputs to quantify GHG emissions or sequestration following land-use changes. More than half of the articles use life-cycle analysis (mostly for impact assessment), whereas biophysical and economic models are used by 20% of the articles.

With regards to climate mitigation impact, peer-reviewed literature does not sign a blank check to non-food biomass. The number of articles finding a decrease in GHG emissions or an increase in carbon sequestration following a diversion of food/feed crops towards non-food products is only 50% higher than the number of articles with opposite conclusions. The probability to find a decrease in GHG emissions is not significantly different between articles with a least one crop which can be used as feedstock for diesel and articles with a least one crop which can be used as feedstock for ethanol.

As the LUC-related carbon intensity of biofuels much depends on where the feedstock is grown and which land-use it replaces, we investigated whether specific land-use change patterns can be tied to certain types of feedstocks. Contrary to our expectations, direct forest and grassland conversion is significantly less often considered for second generation feedstocks or wood. One notable crop-specific feature is that jatropha and palm are more often associated with deforestation than other crops. The location of the diversion however does not generate any clear difference in the origin (forest vs annual crop vs grassland) of direct or indirect land-use change.

All in all, our strategy to go for a high number of articles does not prove more conclusive than the selectiveness of previous reviews. This inconclusiveness may provide grist to the mill of Finkbeiner (2014) who argues that the iLUC concept has little political relevance due to the large associated uncertainty and the necessity to apply it to all land use shifts – including conservation or organic farming – before using it in the specific context of non-food biomass production shifts. We may agree with the latter reason, but not with the former: uncertainty is a strong argument for caution but a poor one to support inaction.

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## Annexes

### *Methods*

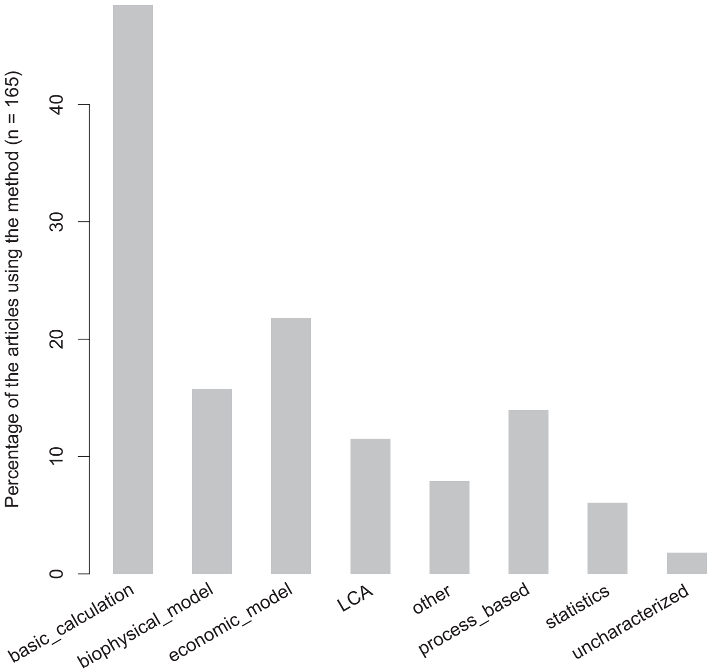


**Fig. 6.13** Methods used for diversion and land-use change assessment

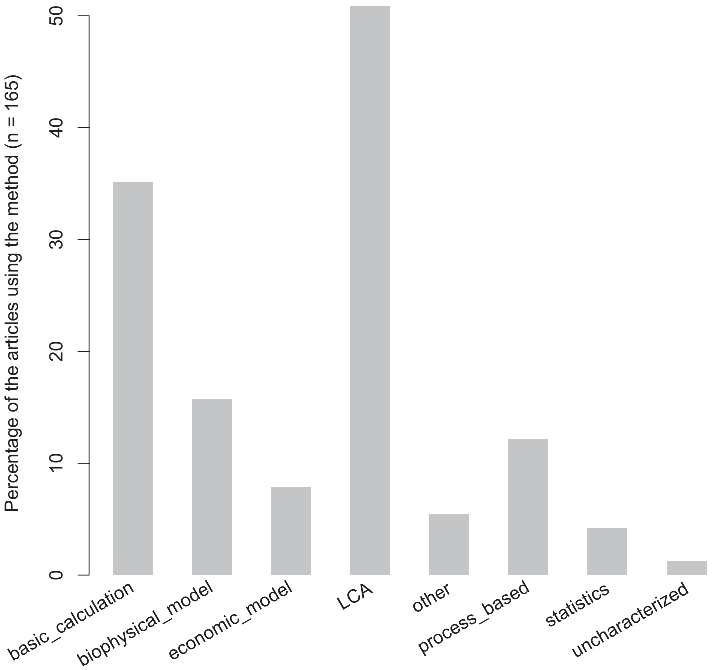


**Fig. 6.14** Methods used for climate mitigation impact assessment

## Publication Year

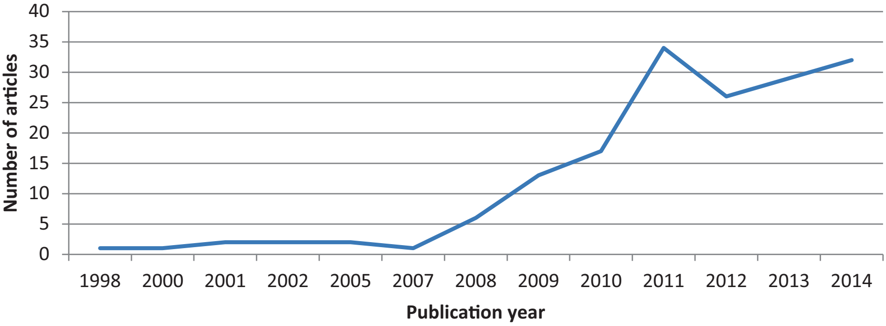


**Fig. 6.15** Publication year of the 162 articles studying the impact of land use change on climate

## Species Studied

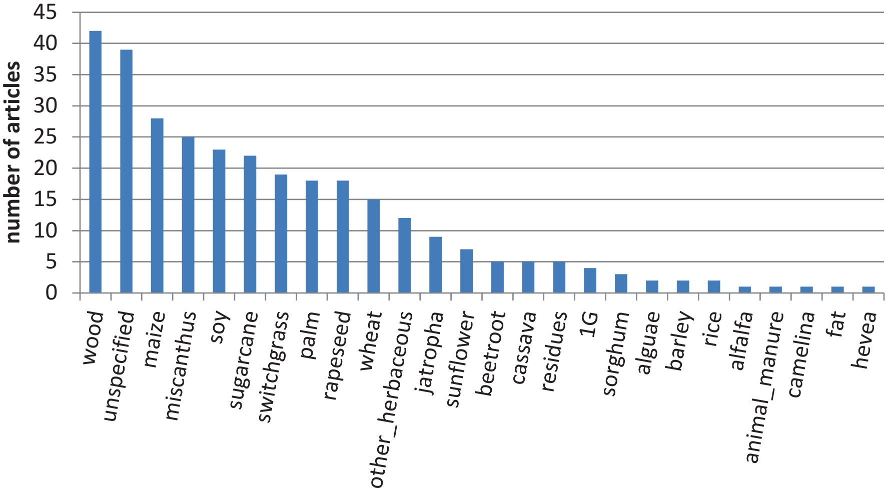
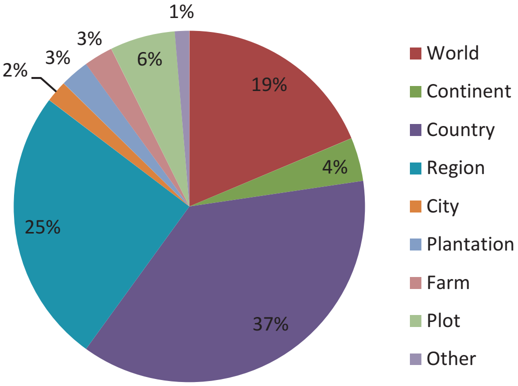


**Fig. 6.16** Distribution of articles among the different feedstocks and feedstocks groups (310 occurrences)

## Resolution of the Set of References

**Fig. 6.17** Scale at which the shift is studied (% of 150 articles for which the scale is specified)



## Climate Mitigation Outcomes of Different Subsets

**Table 6.6** Climate mitigation outcome of different subsets of articles

| | Impact on GHG emissions | | | | |
|---|---|---|---|---|---|
| | decrease | increase | no_variation | variable | Nb of articles |
| Presence of iLUC | 46% | 33% | 0% | 21% | 48 |
| Presence of 1G feedstock | 47% | 26% | 5% | 22% | 93 |
| Presence of 2G feedstock | 34% | 39% | 0% | 27% | 44 |
| Presence of 1G ethanol feedstock | 45% | 32% | 4% | 20% | 56 |
| Presence of 1G diesel feedstock | 52% | 20% | 8% | 20% | 50 |
| Single scenario | 62% | 19% | 5% | 14% | 37 |
| Multiple scenari | 38% | 31% | 2% | 28% | 128 |
| Single species | 49% | 23% | 3% | 25% | 65 |
| Multiple species | 42% | 30% | 5% | 23% | 57 |
| Methods include basic calculations | 40% | 28% | 5% | 26% | 102 |
| Methods include a biophysical model | 46% | 35% | 0% | 19% | 37 |
| Methods include an economic model | 46% | 38% | 0% | 15% | 39 |
| Methods include a LCA | 41% | 24% | 6% | 29% | 85 |
| Methods include a process-based model | 43% | 26% | 0% | 31% | 35 |

E.g. 46% of articles accounting for iLUC find a decrease in GHG emissions

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# Chapter 7
# Review of the Impacts on Air Quality and Human Health of Land-Use Changes Induced by Non-food Biomass Production

**Benoît Gabrielle**

**Abstract** Biomass production has developed significantly in the latest decades to meet the growing needs of the bioeconomy sector. This trend is expected to continue in the near future to substitute dwindling fossil resources. Concerns were recently raised on the consequences of expanding feedstock production on land use worldwide, prompting a surge in scientific publications. These consequences may be analysed through a three-step causal chain relating drivers of feedstock production, changes in land use (LUC), and environmental impacts. Among these, atmospheric pollution or human health impacts, as related to LUC, are rarely evaluated although they are a prime concern for environmental policies and the sustainability of the bioeconomy.

Here, we reviewed current research on the LUC-mediated effects of biomass development on air quality and human health through a systematic survey of literature from 1975 to 2015. Only 17 articles addressing air quality and 9 papers addressing human health were retrieved. Most were published after 2014, implying that these topics only emerged recently. Most studies focused on liquid biofuels (1st and 2nd generation), although bio-materials and bio-electricity were also represented. These studies covered several geographical areas, with an emphasis on Europe and South America. Given the small size of our sample and the diversity of contexts it addressed, it is difficult to evidence clear-cut trends on the impacts of substituting fossil resources with biomass on human health and air quality.. Overall, the benefits of this substitution appeared mixed and dependent on the type of end-product considered. First-generation biofuels were out-performed by their second-generation counterparts, but this trend relies on a low number of references. Life-cycle assessment was the predominant method used to estimate the impacts of biomass development on human health or air pollution. This emerging field warrants further efforts toward more thorough assessments of LUC effects.

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## 7.1 Introduction

Biomass production has developed significantly in the latest decades to meet the growing needs of the bioeconomy sector (whether for bioenergy, biomaterials, or bio-based chemicals), and this trend is expected to continue in the near future to substitute dwindling fossil resources (Chum et al. 2011). Concerns were recently raised around the consequences of land-use changes (LUC) incurred when expanding feedstock production (e.g., Searchinger et al. 2008), and prompted a surge in scientific publications over the past 10 years (see Réchauchère et al., General Introduction, this volume). Attributing LUC to biomass production requires the elicitation of mechanisms explaining the relationship between feedstock production, changes in land use or land management, and their impacts on the environment. These relationships may be analysed as a three-step causal chain: drivers of feedstock production, LUC occurring in response to this production – whether direct or indirect, and environmental impacts involving various dimensions, such as greenhouse gas (GHG) emissions, biodiversity, water resources, soil quality, or human health.

Although the effects of LUC on the GHG balance of biofuels have been extensively documented in the literature (see eg, Broch et al. 2013; Berndes et al. 2013; Bamiere and Bellassen, Chap. 6, this volume), the impacts on atmospheric pollution or human health – as mediated by LUC – is rarely reported. A recent review of “meta-studies” carried out in the context of “land-use science” (van Vliet et al. 2016) fails to mention these issues, implying they have been little researched in this context, whereas impacts on air quality are clearly high on the environmental policy agenda in general (Molina and Molina 2004). Reducing “the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination” is one of the targets mentioned by the Sustainable Development Goals put forward by the United Nations in 2015. Air pollution and human health are also important issues for bio-based products, concerns having been raised on the actual benefits of substituting fossil fuels with biofuels (Chum et al. 2011). For instance, bio-ethanol blends were shown to increase ozone concentrations the troposphere under low temperatures, and thus adversely impact human health compared to pure gasoline in the US (Ginnebaugh et al. 2010). Most of these studies ignore LUC effects associated with feedstock production, although changes in land use or management are likely to affect emissions of primary air pollutants such as nitric oxide or ammonia (Bouwman et al. 2002), toxic contaminants such as pesticides (Foley et al. 2005), or black carbon emissions from slash-and-burn when converting forests.

Here, we set out to review scientific articles dealing with the relationships between bio-based products, LUC, and their impacts on atmospheric pollution and human health, since both impacts are connected and often jointly addressed. The objective was to assess the current extent and foci of such research, regarding biomass feedstocks, its end-uses, and categories of LUC analysed, and to examine possible trends in the outcomes of these studies. In particular, a key question regarded the effect of including LUC on the conclusion of the assessments of substituting fossil-based products with bio-based equivalents. This overview also aimed at highlighting possible gaps with current research, and potential improvement routes in terms of methodology.

## 7.2 Literature Survey

In a first step, we surveyed the scientific literature on LUC (whatever the driving factor) between 1975 and February 2015, and retrieved a body of 5730 articles from two databases relevant to this topic (Web of Science and CAB). All references included keywords related to land-use changes, but another constraint was that references should cover the three steps of the following causal chain: driving factors → land-use changes → environmental impacts. They were selected so as to a mention at least one bio-based end-product, one type of biomass feedstock, and one category of environmental impacts – including atmospheric pollution and human health.

An automated textual analysis of the papers' abstracts, titles and keywords evidenced a series of themes structuring this set of references (El Akkari et al., Chap. 2, this volume), and the subset of papers studying the environmental impacts of biomass/bioenergy through LUC effects was selected. It was further screened manually by a dozen of experts in the fields covered by this literature (economics, ecology, agronomy, forestry, sustainability assessment), and winnowed down to 241 references covering all impact categories. The references pertaining to including atmospheric pollution and human health totalled 17 and 9, respectively, making up less 8% and 5% of the overall body of references on LUC mediated impacts. There was an overlap between the two impact categories, with six articles dealing with both. Thus the total number of articles analysed in the following sections was 20.

All the articles were published after 2008, which was a turning point in LUC-related research (Réchauchère et al., General Introduction, this volume). Most papers (13 out of 20) were published in 2014 and 2015 (the latest year surveyed), implying this topic is still in its infancy. All studies involved several scenarios in terms of feedstocks, end-uses and LUC. One article investigated about a hundred of them, corresponding to 20 different possible LUC scenarios in the US (Daystar et al. 2014).

## 7.3 Feedstock Types and End-Uses Assessed

Arable crops dominated in terms of feedstock types (Fig. 7.1), with first-generation (1G) biofuels as main application, followed by bio-plastics. Lignocellulosic crops came second, with perennial herbaceous species as well as woody ones, in the form

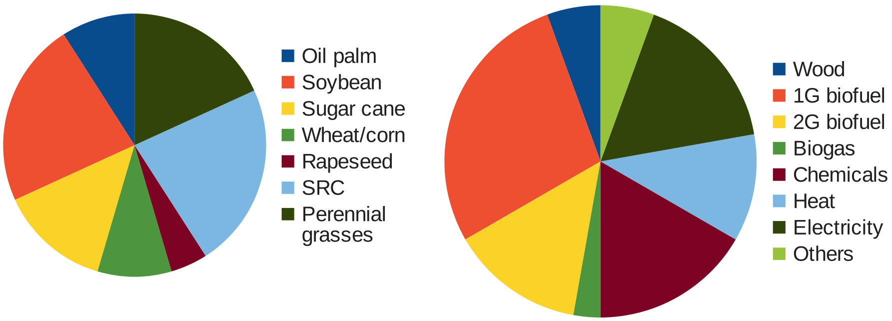

**Fig. 7.1** Breakdown of feedstock types assessed in the literature surveyed (right), and end-uses (left). *SRC* short rotation coppice (poplar, willow, eucalyptus)

of short rotation coppice (SRC). Miscanthus, switchgrass, and poplar SRC were the most frequent feedstocks investigated, with a range of end-uses: combined heat and power, bio-plastics, or 2G biofuels. Liquid biofuels dominated in terms of end-uses, with a 45% share overall (Fig. 7.1). Oil palm was assessed in three articles, in the context of 1G biofuels, but also delivering heat and electricity co-products via the anaerobic digestion of palm oil meal effluent. Four studies involved agricultural residues. This was unexpected since residue extraction from agricultural land does not require additional land for production, in principle, and is thus generally considered neutral in terms of LUC. However, these articles tackled the impact of residue removal on soil quality, as opposed to being returned to the soil (eg, Clark et al. 2013), and also compared this feedstock with dedicated biomass plants. One article combined the conversion of an oil crop (*Brassica camelina*) to bio-diesel, with the use of its co-products (straw and cake) to produce chemicals, following a biorefinery approach (Fiorentino et al. 2014). Most studies compared bio-based products and fossil-based equivalents, but some (2/20) simply focused on the effects of establishing biomass plantations on unproductive land (eg marginal soils).

Europe was the most frequent continent for biomass expansion (40% of the articles), followed by South America (30%) and North America (20%). Most studies were done at national scale, with regional differentiations for about a third of them.

## 7.4 Categories of Land-Use Changes Analysed

A total of 38 scenarios of LUC were reported by the experts who analysed the 20 articles selected in this review. Seven of those were seemingly neutral (e.g., cropland to cropland), and were zeroed by convention in the corresponding matrix (Table 7.1) to focus on more radical shifts such as forest to cropland. This leads to a total of 31 LUC scenarios overall. These involved mostly the conversion of cropland or grassland to perennial biomass plants (14 scenarios out of a total of 31), and the conversion of cropland to grassland, or vice-versa (10 scenarios). Conversion to

**Table 7.1** Matrix of direct land-use changes reported in the 20 articles reviewed

| To from | Forest | Cropland | Perennial crop | Grassland | Wetland |
|---|---|---|---|---|---|
| Forest | – | 3 | 4 | 0 | 0 |
| Cropland | 1 | – | 7 | 6 | 0 |
| Perennial crop | 0 | 0 | – | 0 | 0 |
| Grassland | 1 | 4 | 7 | – | 0 |
| Wetland | 0 | 0 | 1 | 0 | – |

forest was only mentioned twice, while wetlands were affected only once. Only 14 scenarios (out of 31) reported indirect LUC as such in the articles. These mostly pertained to the conversion of forests into cropland, grassland or perennial crops (8 scenarios), and that of grassland (4 scenarios; not shown here). Besides LUC, some changes in land management practices were also reported: intensification and extensification of cropland were mentioned once each, and the conversion to organic farming was mentioned in a fourth of the articles. This emphasizes the importance of this potential shift in terms of environmental impact mitigation, despite its low acreage overall (only 5% of the Uttilizable Agricultural Area was organic in 2010 in Europe; Bellora and Bureau (2013). Note that the impacts of shifting to organic production in terms of land use per se, due to the lower yields itentails in general (Seufert et al. 2012) was beyond the scope of these articles, although this may generate significant LUC effects (see Bellora and Bureau 2013).

In terms of methodology to assess LUC in response to increasing biomass demand, simple methods such as 'basic calculations' dominated, along with the absence of an identifiable methods in a quarter of the articles. Economic models, which are one the major options to assess LUC (Gabrielle et al., Chap. 3, this volume) were only used in one article (or 5% of the studies), while bio-physical models were mentioned in only 3 articles.

## 7.5 Air Pollution, Biomass and LUC: Mixed Outcomes and an Overwhelming Effect of End-Product Types and System Boundaries

Life-cycle assessment (LCA) was the single most used method to assess impacts on air pollution, with an occurrence of 85%. Air pollution was actually reduced to so-called the photo-chemical ozone creation potential (POCP), a commonly-used midpoint impact of LCA. It was calculated with characterization methods such as CML, Impact2002+, and EDIP (see Dreyer et al. 2003) for a comparison of these methods). In the other cases, either no particular methodology was reported, or a simple calculation. LCA was often combined with biophysical models to simulate crop yields and/or emissions of air pollutants, such as nitrogen oxides. Chemistry-transport models, which are heavily used in the investigation and prediction of air

**Table 7.2** Contingency table of the impact of developing biomass on air pollution, depending on the type of end-product generated

| End-product | Counter-factual | Impact on air quality | | | | Total |
|---|---|---|---|---|---|---|
| | | Positive | Negative | Neutral | Variable | |
| 1G biofuel | Fossil fuel | 1 | 2 | 1 | 5 | 9 |
| 2G biofuel | Fossil fuel | 4 | 0 | 1 | 2 | 7 |
| Heat | Fossil fuel | 2 | 1 | 0 | 1 | 4 |
| Electricity | Fossil fuel | 4 | 3 | 0 | 0 | 7 |
| Bio-plastic | Petro-chemical plastic | 4 | 2 | 0 | 0 | 6 |
| Development of biomass crops | Marginal land; current electricity mix and cropland | 0 | 1 | 0 | 1 | 2 |
| Total | | 15 | 9 | 2 | 9 | 35 |

The total number of cases exceeds the number of articles because the latter consider more than one end-product

pollution were never mentioned, although they have been used in combination with LCA in the past (Labouze et al. 2004). Only 2 papers out of 17 included information on the accuracy of impact estimates.

The outcomes of biomass development were highly variable overall: 7 articles concluded to a decline in air pollution, 5 to an increase, and 5 to a variable effect. The outcomes depended on the type of end-product considered (Table 7.2), but also on the types of comparison pursued by the studies. While most of them focused on the substitution of fossil-based products by bio-based equivalent, two compared agricultural biomass and forest feedstocks. One of them concluded to the superiority of forest resources over their agricultural counterparts for the supply of lignocellulose. Another examined the interest of replacing imported palm oil by locally-sourced agricultural products in Canada, and showed import substitutes to be less detrimental to air quality.

In terms of end-products, 2G biofuels and bio-plastics were generally associated with a decrease in air pollution compared to fossil fuels (Table 7.2), while the impact of 1G biofuels was mostly variable. Electricity from biomass generated mixed results, with 4 cases increasing air pollution and 3 cases producing the opposite result. While electricity from biomass is generally ascribed a detrimental impact on air quality because of particle emissions when burning the feedstock (Chum et al. 2011), some cases in our sample involved biogas generation from the co-products of 1G palm oil-based biofuels. Power generation from biogas is less prone to these emissions, and may out-perform electricity generated by the combustion of fossil resources in terms of air pollution (Poeschl et al. 2012).

Two studies lead to conflicting outcomes regarding the substitution of petroleum-based material with bio-plastics (Alvarenga et al. 2013; Liptow and Tillman 2012), although based on the same case study (plastic manufacturing from ethanol produced from the sugar cane in Brazil), and the same category of LUC (grassland converted to sugar cane for the direct part, conversion of Amazonian forests or savannas to grassland or cropland for the indirect effects). Since none of the studies accounted for air pollutants emissions in relation to indirect LUC, the major difference between them lies in the transport of bio-plastic, which is consumed in Europe in the article concluding to the superiority of fossil-based plastic (Liptow and Tillman 2012). The authors also compared the attributional and consequential approaches for the LCA – the second being more favourable to bio-plastics than the first, due to an emission credit granted by the generation of electricity at the end of life of bio-plastics (in Europe).

## 7.6 Human Health Impacts: Scant Data and Exposure Pathways

Only 9 articles dealt with the impacts of bio-based products of human health, with 6 of them being also part of the above-described set of references on air pollution. Thus, there are strong similarities with the latter set in terms of methodologies: LCA was predominant again, being present in all the articles but one (Larsen et al. 2014), which involved a qualitative survey of stakeholders impacted by the development of the oil palm mill in a region of Indonesia. On the other hand, half of the studies involved uncertainty analyses, which were thus more frequent than with the air pollution theme. In terms of scope, most of these studies compared bio-based products (whether liquid fuels, electricity, chemicals or bio-materials) with fossil equivalents. Two exceptions involved the cultivation of camelina, an oil crop, on contaminated soils (Fiorentino et al. 2014), and the development of oil palm in Indonesia (Larsen et al. 2014). It is important to single out these two studies in the analysis of the outcomes since they involve different system boundaries and scope.

Out of the 7 studies comparing fossil and bio-based products, two concluded that the substitution by biomass lead to an improvement in human health, two to detrimental effects, one to neutrality, and two to variable effects. The breakdown was similar regardless of the end-product considered (Table 7.3), with only 2G biofuels presenting an absence of adverse effects, although it is hard to conclude based on only 20 end-product cases overall. There are currently very few literature reviews on the health impacts of bio-based products available. An early article focusing on 1G bioethanol concluded that results on human toxicity "were more often unfavourable than favourable" to this biofuel (von Blottnitz and Curran 2007), due to emissions occurring during the feedstock cultivation and harvesting phases. These studies did not factor in LUC effects, but revealed a similar pattern to that observed here. A more recent review encompassing lignocellulosic biofuels concluded that reliance on herbaceous feedstocks resulted in higher impacts on human health compared to fossil fuels, but that wood or flax shives (an agricultural co-product) had positive effects (Borrion et al. 2012). The way LUC was handled in these studies is not clear from the review, which suggests that variations in LCA outcomes across studies mostly depended on allocation methods (for co-products) and system boundaries. Another study mentioned in this review concluded that bio-materials always

**Table 7.3** Contingency table of the impact of developing biomass on human health, depending on the type of end-product generated

| End-product | Counter-factual | Impact on human health | | | | Total |
|---|---|---|---|---|---|---|
| | | Positive | Negative | Neutral | Variable | |
| 1G biofuel | Fossil fuel | 1 | 3 | 0 | 1 | 5 |
| 2G biofuel | Fossil fuel | 1 | 0 | 0 | 1 | 2 |
| Heat | Fossil fuel | 2 | 0 | 0 | 0 | 2 |
| Electricity | Fossil fuel | 2 | 1 | 1 | 1 | 5 |
| Bio-plastic | Petro-chemical plastic | 2 | 1 | 0 | 1 | 4 |
| Development of biomass crops | Current land use | 0 | 1 | 0 | 0 | 1 |
| Total | | 8 | 6 | 1 | 4 | 19 |

The total number of cases exceeds the number of articles because the latter consider more than one end-product

had lower impacts on human health than their petrochemical counterpart, which was not so clear-cut here.

As could be expected, the two studies examining the expansion of biomass production per se pointed to a detrimental effect on human health, due to increased pressure on otherwise unmanaged land. In the absence of a counterfactual scenario for delivering the service provided by biomass, the value of such results is hard to fathom in practice, other than pointing out at the need to carefully select the land on which bioenergy crops should be established, and to prevent detrimental effects as much as possible by an appropriate management of the plantations.

## 7.7 Conclusion

The impacts of bio-based products on air quality and human health, as mediated by land-use changes are rarely addressed, and represented less than 10% of the body of references addressing the full drivers to impacts chain of biomass development analysed in a recent review (Réchauchère et al., Chap. 1, this volume). Still, the 20 articles retrieved in this article covered a significant range of feedstock types, end-uses, and geographical regions. Liquid biofuels were predominant, but other end-uses such as bio-plastics or electricity were also represented. As a result, arable crops and dedicated lignocellulosic species (perennial grasses and short rotation coppice) were the most frequent feedstocks analysed. Environmental impacts were almost exclusively evaluated by means of life-cycle assessment (or its variant, life-cycle impact assessment), which does not reflect the diversity of assessment methods used to investigate either atmospheric pollution or human health impacts (Steinemann 2000).

Given the small size of our sample and the diversity of contexts it addressed, it is difficult to evidence clear-cut trends. Overall, the benefits of substituting fossil resources with biomass appeared mixed. Despite the fact that only one assessment method was used, which could lead to some degree of bias, it is also clear that the reliability of these estimates is rather low and uncertain, given that this framework is ill-equiped to address air pollution or human health (Hauschild et al. 2008; Bessou et al. 2011). Relying on more commonly-used methods to deal with atmospheric pollution or human toxicity impacts, such as air pollution modeling and epidemiology (Schwartz et al. 2017), or environmental impact assessment (Steinemann 2000), respectively, would be relevant to complement LCA and provide benchmarks. Effects related to indirect LUC – ie occurring outside of the region where the biomass was produced are also difficult to deal with, leading some of the experts who reviewed these articles to question the robustness of their conclusions. This emerging field warrants further efforts toward sounder methodologies and more thorough assessments of LUC effects.

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# Chapter 8

# Review of the Impacts on Biodiversity of Land-Use Changes Induced by Non-food Biomass Production

**Sabrina Gaba**

**Abstract** Over the last few decades, much emphasis has been put on using biomass and other renewable resources for energy production. In a context of increasing human population, global biodiversity decline and rapid climate change, expanding land clearance for bioenergy crop cultivation raises many concerns about the competition for agricultural land use between food, feed, and fibre production. Expanding land for bioenergy therefore challenges the sustainability of agricultural systems as well as its environmental impact. Several studies have attempted to quantify these impacts of land use change (LUC), however they do not take into account the causal chain from "the drivers of LUC to the impact assessment" which is required to understand the underlying mechanism.

The work is part of a global project assessing the impact of LUC toward bioenergy crops cultivation considering the causal chain. Here, we review studies assessing how land-use shifts towards bioenergy crops impact biodiversity. The review first reveals that very few studies have assessed biodiversity by considering the whole causal chain. Despite this, a general consensus emerges on a negative impact on biodiversity of bioenergy crops cultivation. This study also points out the diversity of metrics used to assess biodiversity, from species richness to proxies such as habitat quality. Overall, this review suggests that a sounder quantification of the effect of LUC toward bioenergy crops cultivation could be obtained by using more accurate metrics both for biodiversity (i.e. coupling taxonomic and functional diversity indices, and selecting relevant taxa) and the characterization of the environment (i.e. landscape configuration and composition, and the integration of management practices).

**Keywords** Biofuels · Bioenergy · Biomass · Land-use change · Biodiversity · Landscape configuration · Landscape management · Pollinators · Birds

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## 8.1 Introduction

Agricultural land covers nearly one quarter of the Earth's terrestrial surface (Vitousek et al. 1997) being the principal land use at the French (~ 52%) and European levels (~ 42%). For long, agricultural lands have been managed to provide food, fibre, and wood product. In order to meet a growing demand for these products, human activities disrupted the global environment, resulting in profound and unsustainable alterations to land use, water fluxes, biogeochemical cycles, atmospheric chemistry and distribution and dynamics of biodiversity worldwide (Pimm 1995; Chapin et al. 2000; Lambin et al. 2013). Over the last few decades, due to concerns about the negative impacts of human dependence on fossil resources, much emphasis has been put on relying more on biomass and other renewable resources for energy production Chum et al. (2011) calling for the production of biofuel (liquid fuel derived from plant material). In a context of increasing human population, global biodiversity decline and rapid climate change, expanding land clearance for bioenergy crop cultivation raises concerns about the competition for agricultural land between food, feed, and fibre production, hence challenges the sustainability of agricultural systems.

Expanding land use for bioenergy feedstock production can cause direct land-use changes (dLUC) on a farm or forest plantation as well as indirect LUC (iLUC) through the displacement of previous land uses to other locations. Several studies have therefore been conducted to investigate the consequences of land-use, LUC and iLUC toward non-food feedstock production (reviewed in Fritsche et al. 2010). LUC and iLUC concerns both the production of first-generation liquid biofuels from food crops (such as sugarcane, palm oil, oilseed rape, corn, wheat) and ligno-cellulosic feedstocks for second-generation biofuels (such as miscanthus, switch-grass, salix, and eucalyptus). However, most of the studies investigated LUC (or iLUC) without taking into account the drivers of LUC and their impacts (Van Vliet et al. 2016), thus limiting the ability to elucidate the mechanisms relating feedstock production to LUC and their impacts on the environment.

A project was therefore set up to fill this gap. This study consisted in reviewing the studies that analysed the impact of LUC and iLUC induced by bioenergy crops cultivation as a three-step causal chain: drivers of feedstock production, LUC occurring in response to this demand – whether direct or indirect, and impact assessment along various dimensions, such as greenhouse gas (GHG) emissions, biodiversity, water resources, soil quality, or atmospheric pollution. The review presented here is part of this project and aims to provide an overview of the issues relating to direct and indirect land use changes that could result from growing energy crops and their impact on biodiversity. Biodiversity plays a crucial role in the delivery of a range of ecosystem services such as nutrient and water cycling, pollination and soil formation (Hooper et al. 2005; Balvanera et al. 2014). At the same time biodiversity is increasingly threatened by climate change and human activity through the massive use of pesticides and habitat loss.

## 8.2 Materials and Methods

### *8.2.1 Literature Survey, Definition and Analysis of a Relevant Set of References*

The general review (see Réchauchère et al., Chap. 1, this volume) covers studies (i) published from 1975 to early 2015, (ii) featuring keywords related to land-use changes, (iii) including the three steps of the drivers to impact causal chain, and (iv) in which the types of end-product(s) and biomass feedstocks were specified. At least one category of environmental impacts among the following had to be assessed: climate (including GHG emissions), consumption of non-renewable resources, biodiversity, water resources, soil quality, atmospheric pollution, human health, and ecotoxicity. We performed a comprehensive search on Web of Science and Centre for Agricultural Bioscience last updated in February 2015. It provided a preliminary list of 5730 articles. The abstract, title and keywords of each article were read independently using an automated textual analysis (for more details see Réchauchère et al., Chap. 1, this volume). A subset of articles (i.e. 1785 articles) studying the impact of biomass/bioenergy through LUC effects was further screened by a dozen of experts in the fields covered by this literature (economics, ecology, agronomy, forestry, and sustainability assessment), and winnowed down to 241 references. These were further analysed in details in terms of scope, LUC types, methodologies employed, and overall impacts of biomass production.

### *8.2.2 Description of the Set of Articles*

Among the 241 articles retained by the experts, only 15 articles investigated the impact on biodiversity of land use or land use changes incurred by bioenergy production (Table 8.1). The studies were generally performed in developed countries (Europe and the US). LUC was either directly studied or investigated by comparing the impact of a biomass crop with another land use in the same landscape (e.g. Stanley and Stout 2013). The impact of LUC on biodiversity was a topic more recently addressed in comparison with other impacts in the overall set of articles (see e.g. Bessou, Chap. 4, in this volume on soil quality or Bamière and Bellassen on greenhouse gas emissions, Chap. 6, in this volume) since more than 80% were published after 2009. From a qualitative point of view, the last decade was characterized by the development of studies investigating biodiversity and ecosystem services (Villamor et al. 2014).

**Table 8.1** Description of the studies. An empty indicates that the information was not found in the article

| References | Publication Year | Study Localization | Drivers | Scale | Number of energy crop species | Type of enery crop species | Type of biodiversity metrics |
|---|---|---|---|---|---|---|---|
| Alkemade *et al.* | 2009 | All world regions | Climate change mitigation through energy policy | Continent global |  | Wood | Mean species abundance (MSA) |
|  |  |  | Shift of wood production toward sustainable managed plantations |  |  |  |  |
| Alvarenga *et al.* | 2013 | Brazil (Amazonia) | Production of bioethanol to fit an increasing demand | Region | 1 | Sugarcane | LCIA |
| Baral *et al.* | 2013 | Australia | European settlement in the early 1850s | Region | 2 | Pinus Eucalyptus | Relative capacity of each land use and land cover to support habitat of flora and fauna based on the presence of threatened species, patch size and connectivity. |
| Brandt and Glemnitz | 2014 | Germany | Cultivation of biomass crops for energy supply | Farm | 1 | Maize | Habitat suitability |
| Death *et al.* | 2003 | New Zealand |  | Stream catchments | 1 | Pinus | Species richness, abundance, several diversity and community indexes. |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Einheuser *et al.* | 2013 | US | Demand for biofuel crops with prices not competitive enough with other agricultural production on fields | Watershed | 4 | Canola maize | Habitat suitability estimated with Hil-senhoff biotic index (HBI), family index of biological integrity (family IBI), and number of Ephemeroptera, Plecoptera, and Trichoptera taxa (EPT taxa) |
| | | | Demand and price for biofuel crops is higher than all other agricultural production | | | Miscanthus switchgrass | |
| Engel *et al.* | 2012 | Germany | Cultivation of biomass crops for energy supply | Field | 1 | Willow | |
| Garcia-Quijano *et al.* | 2005 | Belgium | | Region | 5 | Association of oak and Beech Miscanthus Pine Poplar | Species richness |
| Haughton *et al.* | 2009 | UK | | Region | 2 | Miscanthus and willow | Skylark abundance, breeding success, availability of food and habitat diversity |
| Helin *et al.* | 2014 | Scandinavia | | Country | 1 | Reed canary grass | LCIA |
| Lindborg *et al.* | 2009 | Sweden | Cultivation of biomass crops for energy supply | Region | | Bioenergy crops i.e. short rotation coppice, annual energy crops and permanent leys. | Amount of suitable habitat area, number of suitable habitats, and number of connected groups of habitats. |

(continued)

**Table 8.1** (continued)

| References | Publication Year | Study Localization | Drivers | Scale | Number of energy crop species | Type of enery crop species | Type of biodiversity metrics |
|---|---|---|---|---|---|---|---|
| Louette *et al.* | 2010 | Europe | Policy of large-scale second generation bioenergy crops cultivation throughout Europe | Country | 2 | Willow and poplar | Sensitivity scores to land use changes |
| Murdiyarso *et al.* | 2002 | Sumatra |  | From field to region | 1 | Rubber | Species richness |
| Stanley and Stout | 2013 | Irland |  | Field | 2 | Oilseed rape and miscanthus | Abundance and diversity |
| Villamor *et al.* | 2014 | Sumatra | Payments for ecosystem services (PES) schemes to sustain rubber agroforests | Region | 2 | Rubber and oil palm | Species-area relationship |

## 8.3 Results

### *8.3.1 Drivers of Land-Use Change*

Although a wide range of LUC drivers have been investigated in the overall set of articles on LUC and bioenergy, all of those involving biodiversity impact were anthropogenic. The main driver was the cultivation of biomass crops for energy supply (25% of the set of articles). Another important driver studied in the set of articles was the impact of public policies such as climate change mitigation through energy policy, or policies targeting a large-scale second generation bioenergy crops cultivation (Table 8.1).

Considerable attention has been given to annual crops from which biofuels can be produced, including maize, oilseed rape and sugar cane (Table 8.1). However, little attention has been paid to other feedstock options based on stems, stalks, or woody components of trees (so-called ligno-cellulosic feedstocks). Perennial crops, which do not need to be replanted after each harvest, such as grasses and fast-growing trees, were also of studied.

### *8.3.2 Land-Use Change Scenarios*

Several types of LUC were studied in the set of articles (Table 8.2). LUC occurred over a broad range of spatial scales from small territories (ca. 300 km$^2$ in area), through watersheds, to continents (Table 8.1). The majority of the studies (9) investigated the impact of LUC induced by biomass crops cultivation using both retrospective and prospective approaches. The retrospective approach alone was rarely used (only in two studies). Fourteen LUC scenarios were analyzed in the set of articles, the majority of which investigated the conversion of forest into forest, arable land, perennial crop or grassland. As examples, (Alkemade et al. 2009) investigated the impact of an increase in forest plantations to meet the growing demand of 30% wood by 2050 on biodiversity, while Einheuser et al. (2013) and Stanley and

**Table 8.2** Description of the Land Use Change in the set of articles. The number represents the number of scenarios for which a LUC from a land use in column to a land use in row was studied. For example, 3 scenarios studied the impact of a LUC from grassland to forest on biodiversity. Some LUC can occur within a category. For instance, a winter wheat crop (arable crop) can be replace by an oilseed rape crop for energy production

| From To | Forest | Arable crops | Grassland | Wetlands | Artificial land | Perennial crops |
|---|---|---|---|---|---|---|
| Forest | 3 | 1 | 3 | 0 | 0 | 0 |
| Arable crops | 2 | 2 | 2 | 1 | 0 | 0 |
| Perennial crops | 3 | 7 | 5 | 1 | 1 | 1 |
| Grassland | 2 | 0 | 0 | 0 | 0 | 0 |

Stout (2013) were interested in the impact of meadow conversion to second generation biomass crops.

In the set of articles, the drivers generally affected changes in landscape composition. However, LUC driven either by an increase in bioenergy supply or by public policies can also affect landscape configuration. Only two studies among the 15 investigated the impact of LUC on landscape configuration (Engel et al. 2012; Brandt and Glemnitz 2014), that is to say the distribution of new land-uses (aggregation *versus* random) and/or their cultivated area (i.e. patch size for bioenergy crops).

LUC were characterized with three methodologies: (i) models parameterized with data from meta-analyses or literature reviews for most of the articles (e.g. Alkemade et al. 2009; Nelson et al. 2010), (ii) empirical analysis of land cover data (e.g. based on aerial photographs) or (iii) in fewer cases, *in situ* measurements (usually for estimating species abundances).

### *8.3.3 Metrics Measuring Biodiversity*

A variety of metrics was used to analyze the impact of LUC on biodiversity based either on populations, species or group of species or through proxies. In the latter case, biodiversity was addressed indirectly by (i) a valuation of the suitability of the habitats (biodiversity value being higher in grasslands than in plantations (Baral et al. 2013), (ii) the impacts of human activities as proxy of their effects on biodiversity such as the risk of pesticide pollution (Viglizzo et al. 2011) or the artificial change of water balance (Garcia-Quijano et al. 2005), as well as (iii) measurements through life cycle impact assessment (LCIA) in which biodiversity is estimated through land use following (de Baan et al. 2013a). When biodiversity was directly measured, the studies analyzed the change in species richness (i.e. the number of species) or number of families (Louette et al. 2010; Einheuser et al. 2013), in the abundance of a given species (Engel et al. 2012), or the change of groups of species (Stanley and Stout 2013; Brandt and Glemnitz 2014). Species richness was mainly estimated by *in situ* measurements, although species richness was sometimes estimated indirectly using species-area relationship (Preston 1960). Several studies mainly focused on the impact of LUC on a single guild or a smaller number of species to the exception of (Louette et al. 2010) who retained a set of 754 species that were considered as a representative sample of terrestrial European biodiversity. Two other studies also focused on species typical of the studied environments taking into account the species needs in terms of habitat (e.g. cover and vegetation height, amount of food available) and the dynamics of their populations (e.g. breeding period, reproductive success; (Engel et al. 2012; Brandt and Glemnitz 2014)). The species studied were farmland bird species such as skylarks (*Alauda arvensis*) or lapwing (*Vanellus vanellus*) (Brandt and Glemnitz 2014).

### *8.3.4 Methods for Analysis the Impact of LUC*

The impact of the LUC on biodiversity was generally explored with mechanistic models (e.g. Alkemade et al. 2009; Engel et al. 2012; Brandt and Glemnitz 2014; Villamor et al. 2014) or comparative approaches (e.g. biodiversity in arable crop *versus* biodiversity in bioenergy crops (Stanley and Stout 2013)).

Changes in abundance were usually estimated using a reference abundance value. For instance, (Alkemade et al. 2009) quantified the impact of LUC on biodiversity using the remaining mean species abundance (MSA) relative to their abundance in pristine or primary vegetation which are assumed to have been disturbed by human activities for a prolonged period. MSA was estimated from 89 studies selected in the WoS taking into account the minimum area necessary for organisms, and co-variables such as land use (forest plantations, grasslands, agroforestry …). Others, such as Helin et al. (2014), used indicators such as the biodiversity damage potential (de Baan et al. 2013a) or the potential of non-endemic species loss (de Baan et al. 2013b).

### *8.3.5 Impacts of LUC on Biodiversity*

Whatever the metric used, the approach (modeling or empirical analysis), or the organism of interest, studies showed that land-use shifts (i.e. crop or forest establishment) toward bioenergy crops resulted in a significant loss of biodiversity. For example, 18% of species were negatively affected by the production of wood energy; reptiles, butterflies, birds being the most affected (Louette et al. 2010). Losses of 30% of biodiversity were predicted with a 20% increase of agricultural land to produce non-food biomass (Alkemade et al. 2009).

LUC also lead to changes in species community composition through species replacement or change in the relative abundance of the species in the community. For instance, Brandt and Glemnitz (2014) observed an increase of lapwings (*Vanellus vanellus*) and pies backed Shrikes (*Lanius collurio*) due to a potential increase of food availability in the new habitats (here maize grown to provide biofuel instead of winter barley and oilseed rape). Change in the composition of plant communities was also observed across Europe in dLUC from non-forested lands toward second generation bioenergy crops (mainly willow Salix spp. and poplar *Populus spp*.) (Louette et al. 2010), although this effect was much lower than on reptiles, butterflies and birds. The logging of *Pinus radiata* in New Zealand had also a strong effect on the composition of invertebrate communities of streams draining the catchment: species richness decreased, while the total abundance of invertebrates increased resulting in a less even community (Death et al. 2003).

Although rarely tested (in only two studies (Engel et al. 2012; Brandt and Glemnitz 2014), the spatial organization of dLUC had a significant role on farmland birds by changing landscape configuration. This effect was even more important than change in land use as such change in crop richness (landscape composition). An aggregated distribution of bioenergy crops had a greater impact on skylark (*Alauda arvensis*), corn bunting (*Miliaria calandra*), lapwing (*Vanellus vanellus*), whinchat (*Saxicola rubetra*) and red-backed shrike (*Lanius collurio*) than a random distribution (Brandt and Glemnitz 2014), resulting in a stronger population abundance decline. Similarly, an increase in the average field size was associated with a considerable decline in the abundance of skylarks, up to 86% in the bioenergy crop scenario (Engel et al. 2012). These findings also raise questions about the minimum distances between favorable biodiversity habitats to sustain biodiversity. Overall, these results question the type of scenarios that need to be examined when considering the impact of dLUC on biodiversity. For instance, Garcia-Quijano et al. (2005) addressed the environmental impact of dLUC (multifunctional forest, short rotation coppice and miscanthus). They suggested to favour scenarios with little land use and a moderate impact per hectare (e.g. local short rotation coppice) over scenarios with high land use and low impact per hectare (e.g., local multifunctional forest scenario), to reduce the impact of the LUC. Such output could be useful to define management options for biodiversity conservation.

### *8.3.6 Lignocellulosic Crops: A Dual Effect on Biodiversity*

Although we observed a consensus on the negative impact of the implementation of bioenergy crops (1st or 2nd generation biofuels) on biodiversity, lignocellulosic crops') could have a beneficial effect on biodiversity compared to arable crops. For example, Einheuser et al. (2013) have demonstrated a positive impact of bioenergy crops, such as miscanthus, switchgrass, and native grasses, compared to arable crops on macroinvertebrates through the upgrading of water quality. However, this effect was balanced by the negative impact of the cultivation of these bioenergy crops on fish species through a detrimental effect on the quality of the water draining from the field (Einheuser et al. 2013). This highlights the importance of simultaneously considering several guilds. Replacing winter wheat by miscanthus crops can also result in an increase in the abundance of hoverflies (up to 17%) or wild pollinators (Stanley and Stout 2013). This result was expected since miscanthus crops have abundant floral units that provide nectar and pollen resources for pollinators, which is not the case of winter wheat. The same results were observed when increasing rape crops for bioenergy production instead of alternative crops without floral resources. Therefore, bioenergy crops can be beneficial to pollinators in landscape with poor floral resources, when instead of non-flowering crops.

## 8.4 Discussion

Two major findings emerged from this literature review on the impact on biodiversity of LUC toward bioenergy crops: the unexpected small number of studies on the impact of LUC on biodiversity, and the large consensus on the negative impact of LUC on biodiversity.

The limited number of studies investigating the impact of LUC toward bioenergy crops on biodiversity can be explained by the delineation of the set of articles. It was performed to fit specific criteria among which the necessity to analyze the LUC toward bioenergy crop as a three-step causal chain (drivers of feedstock production, LUC occurring in response to this demand, and impact assessment). Indeed a recent study found 59 meta-studies that assessed the impact of land use in the broader sense on biodiversity, species richness or related indicators are dominant (van Vliet et al. 2016). Therefore, we may expect that more articles investigating the impact on biodiversity of LUC due to bioenergy crops if we relax some criteria. However, this number of studies may remain limited compared to the studies assessing the impact of LUC due to energy crops on air, water or climate. Indeed, energy crops have been implemented to reduce the environmental footprint of fossil energy such as the emissions of $CO_2$ (see Bamière and Bellassen, Chap. 6 and Réchauchère et al., Chap. 1, this volume).

The consensus on the negative impact on biodiversity of LUC toward bioenergy crops is in accordance with outcomes of earlier studies assessing the impact of bioenergy crops cultivation as well as those investigating the impact of land use or LUC for food production on biodiversity (Mendenhall et al. 2014; Newbold et al. 2015). Similarly to food production, cultivating energy crops generally required the conversion of natural or semi-natural habitats into cropland. However forests or semi-natural habitats provide food and shelter for many organisms (Tscharntke et al. 2012), and are thus important to sustain biodiversity. Consequently, annual crops, perennials grasses and woody species cannot be considered as similar with respect on their effect on biodiversity, and separate assessment of the effects of this different LUC needs to be performed.

The analysis of the set of articles raises several methodological questions. Most of the studies used qualitative or empirical relationships between habitat characteristics and biodiversity, species richness or changes in average local species abundance according to global repository (e.g. MSA). Species richness, for instance, may not be sufficient to accurately assess this impact of the LUC. Species richness, i.e. the number of species, does not take into account all aspects of biodiversity such as species turnover, or change in species abundance. For instance, LUC may change community evenness by increasing the number of rare species, without affecting or only to a slight extent species richness. Moreover, none of the 15 articles investigated the effect of implementing bioenergy crops on the functional diversity although it can be a reliable proxy for the processes driving community assembly

(McGill et al. 2006) or the role of biodiversity on ecosystem functioning (Diaz et al. 2011). Using a set of metrics covering species richness, species relative abundance and functional diversity would be a useful approach to consider simultaneously the impact of LUC on biodiversity and its consequences on ecosystem functioning.

Most of the assessments of the impact of LUC on biodiversity were performed with mechanistic models or life cycle impact assessment. The outcome of the studies mainly relies on the values of parameter estimates which were generally taken from the literature. However, none of the articles in the set we identified here included a sensitivity analysis to evaluate the robustness of their results with regard to the parameter values. Moreover, the modeling approach usually considered fixed landscapes. Agricultural landscapes are highly variable environments that change rapidly from year to year because of annual crops (among which first generation biofuel feedstocks). These environmental changes can greatly affect the demographic characteristics of organisms, because of changes in the availability of resources or habitats. Therefore, including the temporal dynamics of the landscape, even for assessing the impact of perennial crops, may be very valuable to investigate the impact of energy crop on biodiversity. Improvement is that needed while using mechanistic models or LCA for assessing the impact of LUC on biodiversity. Seven best-practice recommendations that can be implemented immediately to improve LCA models have been recently proposed based on existing approaches in the literature (Curran et al. 2016).

In addition, the dynamic nature of biodiversity was rarely (if at all) included in the analyses. In fact, environmental changes induced by LUC can be temporarily buffered depending on the response time of organisms. For instance, large organisms such as birds or organisms with resting stages respond with a significant time-lag. Similarly, few studies include population dynamics and demographic parameters. In the set of articles, only two studies assessed the impact of LUC toward bioenergy crops using farmland birds such as the skylark. The use of birds in these studies was motivated by the fact that birds have been adopted as indicators of the quality of landscape and habitat conditions by the European Union (Furness and Greenwood 1993; BirdLife International 2010). Indeed, birds are almost the top of the food chain and are therefore directly affected by changes at all levels within this chain (Furness and Greenwood 1993). Therefore, since environmental changes are difficult to measure directly, they can be inferred through the analysis of bird populations dynamics (BirdLife International 2010).

Finally, the analysis of the set of articles highlighted the need to incorporate the effect of changes in landscape configuration induced by the establishment of bioenergy crops and their cultivation. Indeed, some organisms are more affected by the spatial organization of landscapes or the size of fields (Fahrig et al. 2011). The analysis of the separate effects of landscape composition and configuration on biodiversity, functions and provision of ecosystem services is therefore also a major issue for the sustainable management of agricultural landscapes. Attention should also be paid to feedstock management since agricultural practices such as tillage, fertilizers or pesticide use are known to significantly affect biodiversity (e.g. wild plants e.g. Gaba et al. (2016)); pollinators e.g. Dicks et al. (2015); soil micro-organisms e.g. Levine et al. (2011). For instance, the comparison of arable crops that do not pro-

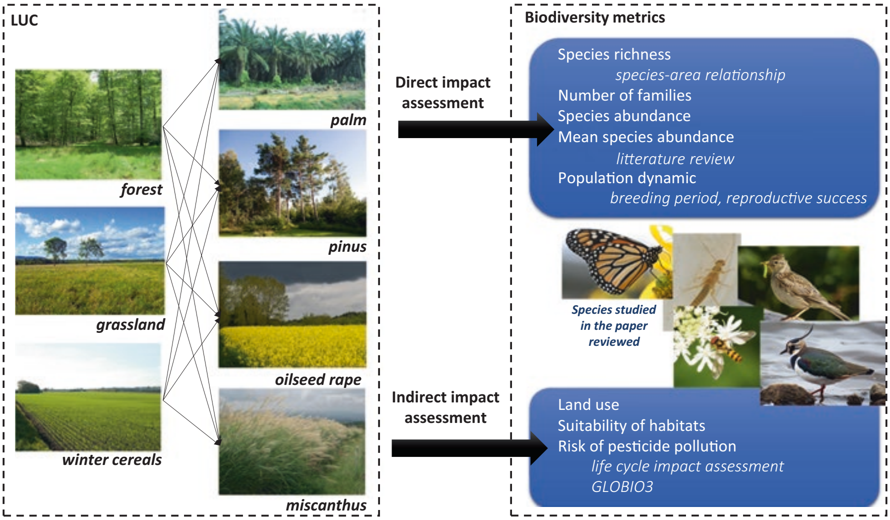

**Fig. 8.1** Synthetic representation of the LUC and biodiversity metrics used either for a direct or indirect assessment in the set of articles reviewed (see Table 8.1 for details on the individual studies). The words in italics on the right panel indicate the methods used to estimate the metrics

vide floral resources for pollinators with miscanthus or oilseed rape was shown to be beneficial for insect pollinators. To go deeper, futures studies should investigate the mid-term effects of these crops by taking into account agricultural practices such as the application of insecticides (Henry et al. 2015), the reduction of herbicides applications or the implementation of field margin to increase weed species abundance (Requier et al. 2015) known to strongly affect the dynamics of pollinators or beneficial insects.

To sum up, a multiple scale assessment of biodiversity (at field and landscape scales) is needed due to the year-to-year variations in landscape composition and configuration. Consequently, a time perspective is also needed, especially in the case of LUC which are generally associated with habitat fragmentation. Indeed, little is known on the occurrence of extinction debts across ecosystems and taxonomic groups as well as the temporal and spatial scales at which extinction debts occur (Cousins 2009; Kuussaari et al. 2009). This also calls for a multiple taxa assessment, which can be subsequently translated into multifunctionality and ultimately into multiple services delivery (Fig. 8.1).

## 8.5 Conclusion

This analysis revealed the small number of studies on the impact of bioenergy crops on biodiversity that account for the entire causal chain: from drivers to impacts. This could lead to an extreme lack of knowledge on LUC-mediated impacts of bioenergy development on biodiversity. Despite this small number of studies, a consensus emerged on the negative impact of LUC toward bioenergy on biodiversity, and this whatever the methodology or the biodiversity metric used. In already intensively managed ecosystems, however, replacing winter cereals by bioenergy crops can favored pollinators through the availability of floral resources. Future studies need to better characterize biodiversity by using relevant metrics exploring the various facets of biodiversity (species richness, species abundance, functional diversity …). Moreover, since species of different taxa may respond differently to changes in landscape composition and configuration, these studies should investigate the impact of LUC toward bioenergy on several species covering the trophic network, including microbial biodiversity. As monitoring several species is not always possible, an alternative could be to focus on farmland birds or emblematic bird species, i.e. those which can be considered umbrella species in the sense that their habitat requirements cover those of many other species. In other words, these species have such specific habitat conditions requirement that when they are met, they cover those of many other species. Coupling models with long-term monitoring of biodiversity is therefore a promising avenue of research to improve knowledge on LUC on biodiversity at multiple spatial and temporal scales.

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# Chapter 9
# Review of the Impacts on Nonrenewable Resources of Land-Use Changes Induced by Non-food Biomass Production

**Patrice Dumas**

**Abstract** Research addressing non-food biomass production from the perspective of land-use change and environmental impacts has expanded considerably since 2008. An exhaustive literature review followed by the identification within the resulting corpus of all references seeking to quantify the consumption of nonrenewable resources yielded 29 articles, which were then examined in detail. Our goal was to describe, as precisely as possible, the methods and results of published research addressing land use change as it relates to the consumption of nonrenewable resources. We found that these articles were in fact more focused on the assessment of other environmental impacts, primarily greenhouse gas impacts, with fossil-fuel use appearing as a collateral result. All the articles employed a life cycle analysis approach; all considered the question of fossil-fuel consumption; and all concluded that a reduction in fossil fuel use was achieved through the substitution of biomass energy. According to the findings of this sub-corpus, biofuels produced from lignocellulosic biomass appear to be most effective in terms of reducing environmental impacts, but few direct comparisons with first-generation biofuels have been made. In general, differences in methodologies and in the assumptions adopted for different studies, particularly with respect to land-use change parameters, make comparisons among the selected studies difficult.

**Keywords** Nonrenewable resources · Biofuels · Bioenergy · Biomass · Land-use change · Greenhouse gas · Fossil fuel

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## 9.1 Introduction

The production of biomass for energy use, particularly biofuels, has expanded significantly over the past decade. A number of public policies and programs have supported this development, and these trends are likely to continue as fossil-fuel resources become more scarce (Chum et al. 2011). The land-use requirements of non-food biomass production can tip the balance on its overall environmental impact, however (Searchinger et al. 2008; Fargione et al. 2008). A substantial literature considering this question has emerged since 2008 (Réchauchère et al., Chap. 1, this volume). The environmental impacts of agricultural systems reoriented towards the production of non-food materials may be analyzed by looking at three steps in a causal sequence or chain. The first step is a change in agricultural production in response to increased demand for non-food materials, with crops being dedicated either partially or entirely to new, non-food uses. Such a change in production type or crop use is referred to as a reorganization. Land-use changes (LUC) resulting from such a reorganization, whether direct or indirect, constitute the second link in the causal chain. The third link corresponds to the environmental impacts resulting both from the new production system and from the land-use change enabling that production system. Impacts may relate to greenhouse gas (GHG) emissions, biodiversity, water resources, nonrenewable resource consumption, soil quality, and/or various types of contamination (e.g. acidification).

While a number of literature reviews have sought to assess this research area (Berndes et al. 2013; Broch et al. 2013), no systematic analysis of the full causal sequence, from reorganization to environmental impacts, addressing multiple impact categories, has appeared to date. Indeed, one review of this material noted a lack of sufficient attention to the question of land use, as well as a disconnect between the study of land-use reorganizations and their environmental consequences (van Vliet et al. 2016). Other types of agricultural reorganizations would also be interesting to consider, such as those resulting from increased food demand or dietary changes (Tilman et al. 2011; Bajzelj et al. 2014) or those linked to urban growth. However, a review of the literature on the causes and consequences of land-use change since the 1970s suggests that the question of biomass for energy production is the area of greatest interest and concern, particularly given the significant role of public policy decisions in encouraging such reorganizations. It is therefore this type of reorganization we will focus on here.

Non-food biomass production is implicated in discussions of diminishing nonrenewable resources since agricultural biomass can be substituted for fossil fuels via the production of biofuels or bio-electricity. Other nonrenewable resources are also used in agricultural production, especially mined phosphorous used as a fertilizer. Few studies have specifically examined this impact, however, despite the fact that phosphorous fertilization is often accounted for in the analyses. Consumption of nonrenewable resources relates primarily to the agricultural phase and processing phases for biomass energy production, rather than to the associated LUC. Some LUC implications may be involved, however, including resources utilized to bring about the LUC (particularly for the development of infrastructure), or alterations in the distance agricultural products are transported. Changes in agricultural intensification and corresponding changes in the use of fossil resources, whether direct or indirect (e.g., for the manufacture or mining of fertilizers) may also result from the reorganization of agricultural systems. One angle for analysis of the selected sub-corpus is to assess to what extent the studies account for these specific changes in resource use as a result of LUC.

The impact of biomass energy production on nonrenewable resource use has been the focus of a number of literature summaries, typically looking at the efficiency of biomass energy production in terms of substitution effects (Bureau et al. 2010; Djomo et al. 2011). The question of LUC has not been examined closely in these reviews, however: while LUC are recognized as important in the assessment of GHG emissions, the nature of the LUC either appeared too uncertain in the case of one review (Bureau et al. 2010), or were too weakly represented in the surveyed research in the case of the second review (being considered in just two out of 26 selected references) (Djomo et al. 2011) for detailed examination. It is interesting to study what the more recent articles in our sub-corpus have to say about LUC effects and how these compare to earlier research focused on nonrenewable resource use.

The larger objective of the current review is to analyze the existing literature on non-food biomass production, including LUC effects and impacts on nonrenewable resources. We will begin by presenting the methods use to select the corpus. Next, we will characterize these studies in terms of geographic coverage, reorganization type, non-food crop type and production output. We will then examine the types of LUC considered, impacts on nonrenewable resources, and the relationship between these impacts and other impacts, particularly GHG emissions. Although our analysis will focus on nonrenewable resources, it may be readily compared with the other analyses in this collection (centered on environmental impacts, GHG emissions, soil quality, contamination of various types, biodiversity, and water resources) since it makes use of the same corpus, follows the same methodology, and is similarly interested in LUC and reorganizations in favor of non-food biomass production.

## 9.2 Literature Review, Selection and Analysis of a Scientific Corpus

Our first step was to extract all articles relating to LUC published between 1975 and 2014 from the Web of Science database, with supplemental searches of the CAB database. This produced a list of 5730 references. In addition to featuring keywords relating to land use, the selected articles had to encompass all three links in the causal chain from reorganization to impacts, including reference to a non-food output, a type of biomass, and at least one of the following impacts: climate (including GHG emissions), consumption of nonrenewable resources, biodiversity, water resources, soil quality, atmospheric pollution, human health and ecotoxicity.

An automated textual analysis of abstracts, titles, and keywords allowed us to identify a series of themes structuring this group of articles (El Akkari et al., Chap. 2, this volume) This in turn made it possible to select the subgroup of articles addressing impacts of non-food biomass production via LUC. The resulting group of 1785 articles was then reviewed manually by a dozen experts in relevant fields (economics, ecology, agronomy, forestry, and sustainable development), reducing the sub-corpus to 241 references. These articles were then analyzed in detail with respect to subject, types of LUC, types of reorganization, methodologies employed, and impacts considered.

## 9.3 Description of the Corpus

Twenty-eight articles (out of 241) addressed the issue of the exhaustion of nonrenewable resources. A single article addressed the consumption of finite reserves of phosphorous; all the others focused on fossil-fuel use for the production of energy and synthetic fertilizers. All 29 articles were published in 2010 or later, with 5 or 6 articles appearing per year from 2011 on.

The single article on the exhaustion of phosphorous described changes in land use over the past 50 years in Argentina, without explicitly focusing on reorganizations toward the production of non-food biomass. The article was retained in the corpus, however, since it was the only article to consider this of aspect of nonrenewable resource use. A statistical approach was used to determine that agricultural intensification had resulted in a loss of organic matter, nitrogen, and phosphorous in soils and a negative impact on wildlife habitat. Thanks to changes in tillage methods (with a shift from conventional tillage to reduced tillage or no-till), however, soil erosion rates are now lower than they were in the mid twentieth century (Viglizzo et al. 2011).

## 9.4 Agricultural Reorganizations in the Corpus

In terms of the geographic scope of the sub-corpus, Europe was strongly represented, with 11 references; as were the Americas, with six articles on Brazil, five relating to the United States, two on Argentina, and one on Mexico. Australia, China, and Vietnam were also represented. No studies relating to the African continent were found in the corpus, and Asia was poorly represented, despite that continent's importance in economic, demographic, and agricultural terms.

As shown in Fig. 9.1, a quarter of the studies do not specify their level of analysis. Where this is specified, it corresponds to the farm level or smaller (farm, plot, or plantation) for six articles, intermediate levels (provinces, regions) for five studies, the country level for eight studies, and the continental level for one study. Since all

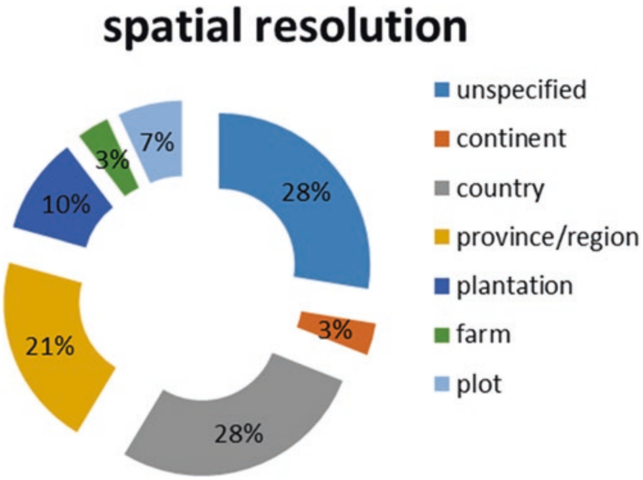

**Fig. 9.1** Distribution of research articles based on scale of analysis

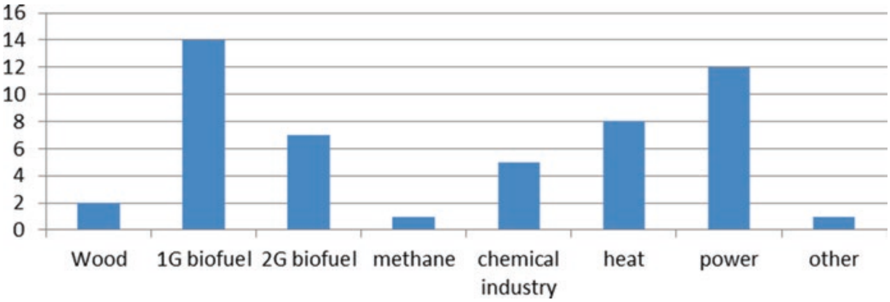

**Fig. 9.2** Distribution of research articles by product type and biomass source

the studies employ a Life Cycle Analysis (LCA) approach, differences in scale are not necessarily relevant as a differentiating factor (LCAs being representative sector analyses).

Biomass sources following agricultural reorganization are divided between harvested grain crops and entire plants, wood, and residues. Final products are likewise varied, with first-generation biofuels, second-generation biofuels, electricity, heat, and products for industrial use, the latter categories being somewhat less represented and making use of both residues and grains (Fig 9.2). Product or output diversity is of course linked to the diversity of biomass sources, with first-generation biofuels being produced from grains and electricity and second-generation biofuels being produced from crop residues, entire plants, or wood.

The role of public policy or legislation as a determinative or contextual element is cited in 15 out of 29 articles. Six of these 15 articles contend that the agricultural reorganizations in question are motivated by public policy decisions.

Four references use an economic model to determine the type and the scale of the reorganizations. In most cases this is the Global Trade Analysis Project (GTAP) model, a multi-region, multi-sector general equilibrium model. Data used to quantify reorganizations are varied, including scientific references (13 articles), expert opinion (10 articles), and data (11 articles).

## 9.5 Land-Use Changes

Direct land-use changes are described in Table 9.1. These conversions correspond to the production of biomass sources as described in the reorganizations, with conversions both into arable crops for first-generation biofuels and into perennial crops for other types of reorganizations. Conversions into arable crops are made from forests or grasslands in equal amounts. There are many examples of reorganizations without a land-use change into or out of arable production (e.g., when cereals are redirected from food use to energy use). Such situations imply the existence of indirect LUC (with no direct LUC) as result of these shifts. Perennial crops are generally established on former grasslands (11 cases) or in place of arable crops (9 cases). Sometimes they take the place of forests (5 cases); in one case they are established in a former wetland.

Indirect changes in land use are less frequently reported, and relate primarily to transitions from forest into arable crops or from grasslands into arable crops (Table 9.2). This low representation of indirect land-use change in fact corresponds to a number of different situations. In four studies, no indirect LUC is reported, despite the fact that the articles describe a replacement (and hence imply a displacement) of arable crops (Cavalett et al. 2013; Malca and Freire 2012; Panichelli et al. 2009; Liu et al. 2013). In other situations, crop residues are used, so no land-use change *per se* is assumed. Finally, and particularly for the production of lignocellulosic biomass, in some instances only direct land-use changes are considered, with new production taking the place of uncultivated land, grasslands, forests, marginal land, or, in some cases abandoned land, contaminated soils, or saline soils. Indirect LUC linked to the conversion of grasslands is almost never examined. If such grasslands were previously used for ruminant grazing, one must account for the displacement of the grass resource; thus if indirect land-use change is not con-

**Table 9.1** Direct land-use change

| Before /After | Forest | Arable land | Grassland | Wetland | Developed land | Perennial crops |
|---|---|---|---|---|---|---|
| Forest | 0 | 4 | 0 | 0 | 1 | 5 |
| Arable land | 1 | 0 | 1 | 0 | 1 | 9 |
| Grassland | 1 | 5 | 0 | 0 | 1 | 11 |
| Wetland | 0 | 0 | 0 | 0 | 0 | 1 |
| Developed land | 0 | 0 | 0 | 0 | 0 | 0 |
| Perennial crops | 0 | 1 | 0 | 0 | 1 | 0 |

**Table 9.2** Indirect land-use change

| *Before / After* | Forest | Arable land | Grassland | Wetland | Developed land | Perennial crops |
|---|---|---|---|---|---|---|
| Forest | 0 | 4 | 2 | 0 | 0 | 2 |
| Arable land | 1 | 1 | 1 | 0 | 0 | 0 |
| Grassland | 0 | 4 | 1 | 0 | 0 | 2 |
| Wetland | 0 | 0 | 0 | 0 | 0 | 1 |
| Developed land | 0 | 0 | 0 | 0 | 0 | 0 |
| Perennial crops | 0 | 0 | 0 | 0 | 0 | 0 |

sidered in these cases, there is an assumption that the converted grasslands are ungrazed. None of the articles consider an alternative agricultural use of lands replaced via a direct LUC – for example, afforestation of grasslands, or the use of marginal lands for livestock grazing – which is understandable given the focus on reorganizations for energy biomass. In five studies, indirect LUC are determined at the global level; the remainder relate primarily to South America. Three references determine indirect LUC through the use of an economic model; the remainder make use of consequential LCA.

Data used to quantify LUC are in most cases drawn from the literature (20 studies), but also from land use data (8 studies), expert opinion (7 studies) and a range of other sources (11 studies). Most studies make use of at least two sources of data. Methodologies used to quantify LUC are primarily simple calculations. It should be noted that this review of methods for LUC analysis applies mainly to direct LUC, since, as noted earlier, indirect LUC may also be analyzed using economic models (3 studies).

## 9.6 Impacts of Land-Use Change on the Consumption of Nonrenewable Resources and Other Environmental Factors

The methods used in the studies considered here are overwhelmingly based on LCA, generally complemented by various methodologies for impact quantification, especially the process-based models that are used to assess changes in soil carbon (CENTURY, IPCC methods). With respect to nonrenewable resource use, studies consistently report a reduction in fossil-fuel consumption when bioenergy is substituted for fossil-based energy resources or when bioplastics are substituted for petroleum-based plastics. One study confines itself to the agricultural production phase and does not consider substitution effects; in this case, not surprisingly, a more significant reliance on fossil resources is reported. It would have been interesting to find a study quantifying nonrenewable resources used directly in LUC – for example, nonrenewable resources required to create the infrastructure necessary for the agricultural use of marginal lands, or fuel consumption used to transport agricultural goods from new production areas. No study appears to have attempted this, however. The LCA literature shows a fairly weak impact of transport on the consumption of nonrenewable resources, which could explain why this question has not been studied in more detail. Few studies have looked at the differences in nonrenewable resource consumption for first-generation vs. second-generation biofuels. We can observe, however, that the production of corn-based ethanol requires significant amounts of fossil-based energy use, whereas sugarcane (thanks to its lignocellulosic byproduct, bagasse) or switchgrass (*Panicum virgatum*, a lignocellulosic perennial crop) require much less (Wang et al. 2011).

These conclusions are in line with Djomo et al. (2011), who found a clear substitution effect across six studies of bioelectricity production using willow and poplar. Conversely, Bureau et al. (2010), looking exclusively at first-generation biofuels, identify less favorable scenarios with respect to biofuel production using soybeans, sunflowers, or corn, with some studies reporting net energy requirements for the sector. The gap between these two conclusions is not easy to assess given that they make use of different research materials. Two possible explanations may be offered, however. First is the difference in time frame, with the Bureau et al. (2010) literature review conducted the year of the first reference within the selected corpus. Technological innovations may be responsible for an improved efficiency of biomass energy in terms of fossil resource use (Wang et al. 2011). Another explanation could be possible bias in the selection of case studies. Since the majority of impact assessments that account for LUC are focused on GHG emissions, it seems possible that such assessments tend to restrict themselves to sectors where GHG emissions appear to be reduced when LUC are not accounted for.

Greenhouse gas emissions have been widely studied. In most cases, we see reductions in GHG emissions compared to a fossil-based reference where biofuels or bioplastics are substituted for nonrenewable resources, but this finding is not universal. Where there is a substitution for fossil energies, as described above, all scenarios are associated with a reduction in fossil resources consumed. Emissions from the combustion of fossil fuels are likewise reduced, with differences in the carbon composition of different combustible materials generally being not very important. If GHG emissions exceed those from fossil energies, it is necessarily due to emissions from elsewhere in the system, in this case carbon emissions resulting from LUC. Effects on carbon stored in the soil and in biomass can be significant. Thus, the replacement of forests by crops is associated with significant increases in emissions (Dunn et al. 2013; Reinhard and Zah 2011), while the replacement of grasslands by miscanthus or by palm plantations results in carbon storage (Souza et al. 2012; Brandao et al. 2011; Delivand and Gnansounou 2013).

Bamière and Bellassen, Chap. 6 in this volume, study LUC and GHG emissions in detail based on a larger number of articles (162 references), using the same methods for selection of the corpus. A meta-analysis of this topic (El Akkari et al., Chap. 2, this volume) investigates the determinants of GHG emissions in more detail. Here we will limit ourselves to a few observations with respect to GHG emissions as reported in the 29 articles in our selected corpus.

Ultimately, second-generation biofuels usually result in lower emissions relative to a fossil-resource baseline, particularly if one assumes that the replaced ecosystems (in the case of direct LUC) are low in carbon and that there are no indirect LUC. Where there are indirect LUC for second-generation biofuels, emissions can be higher than the fossil-resource baseline, as shown in one study (Tonini et al. 2012). First-generation biofuels can result in more emissions than the fossil-resource reference when land-use changes are taken into account, although the selected articles show a tendency toward reduced emissions. Studies that discuss their choice of assumptions (Wang et al. 2011) or that include sensitivity analyses with respect to land-use change and related emissions demonstrate that this aspect of the assessment is highly uncertain and thus may be determinant (Brandao et al. 2011; Reinhard and Zah 2011). Emissions of $N_2O$ in the agricultural phase are also uncertain and are a major source of GHG for this phase. Decisions as to how to allocate byproducts are also very important (Benoist et al. 2012). Nevertheless, "excess" emissions compared to a reference level cannot be attributed to a single factor, since all contributions play a role.

Classic impact methodologies from the LCA literature (CML, Impact 2002+) are employed fairly regularly within the selected articles, but we also find simple calculations (5 studies), and modeling of biophysical processes, especially for soils (4 studies). The studies also assess impacts on soils (carbon levels, levels of soil organic matter) in at least 13 of the 29 references; eutrophication, in 12 references; acidification, in 11 references; pollution, in 9; and impacts on human health in 7 references.

Among the 241 articles analyzed in detail, 162 consider GHG emissions. A large number of these articles could also have reported fossil fuels used and phosphorous consumed. The fact that they do not suggests that studies that consider LUC tend to focus more on GHG emissions. Reading these articles in detail confirms this general impression. This literature is characterized by the effort to expand the system beyond the first step in the causal chain toward impacts, particularly by accounting for LUC in tallying GHG emissions associated with the production and use of non-food biomass. Assessments of the use of nonrenewable resources are essentially a byproduct of this analysis. This situation helps explain the absence of any assessment of nonrenewable resource consumption connected to LUC.

Finally, it should be noted that the boundaries of the systems considered are often dissimilar, particularly (but not only) in terms of accounting for indirect LUC. Different assumptions are also made with respect to the allocation of byproducts, how LUC are amortized over time, and other methodological questions. It can thus be difficult to draw conclusions from multiple studies by looking exclusively at the reported findings, even when all the studies follow an LCA approach.

## 9.7 Conclusion

The 29 research articles reviewed here, selected through a comprehensive survey of the literature, describe impacts on nonrenewable resources of land-use change and the reorganization of agricultural systems toward the production of non-food biomass. All make use of LCA, and all also report GHG emissions. They relate primarily to European and American contexts, but consider a diverse range of biomass sources and outputs – including first-generation biofuels, second-generation biofuels, electricity production, bioplastics, biochemicals, and heat – as well as a variety of direct LUC. Many studies addressing GHG emissions could also have reported impacts on nonrenewable resources, but it would appear that research efforts seeking to account for LUC tend to be focused on GHG emissions, with impacts on nonrenewable resources appearing as a collateral research result. We thus find little overlap between the articles selected here and two allied bibliographic summaries that did not include LUC as a selection criterion (Bureau et al. 2010; Djomo et al. 2011). In the results from the corpus reviewed here, first generation biofuels need fewer fossil resources than in Bureau et al. (2010).

We can further note that the direct impacts of LUC on nonrenewable resource consumption is never evaluated. Infrastructure development for the LUC, changes in the distances traveled by agricultural goods, and changes in agricultural intensification in connection with LUC could also be considered in future studies analyzing these questions. Such an approach could shed light on the controversial subject of the environmental impacts of the re-localization of consumption, including the use of nonrenewable resources.

These studies consistently report a reduction in the exhaustion of fossil resources when bio-energies are substituted for fossil energies or when bioplastics are substituted for petroleum-derived plastics. As a general rule, GHG emissions fall relative to the fossil-fuel baseline, but this is not always the case since the LUC-linked emissions must be added to the emissions resulting from energy used for biomass production, and thus total emissions may be higher than the fossil-fuel reference despite a reduction in fossil energy consumption. According to this sub-corpus, first-generation biofuel sectors using cereal grains or sugars tend to show higher GHG emissions than second-generation sectors using lignocellulosic biomass. Depending on the crops and the transformation processes involved, they may also consume more fossil resources. Conclusions are difficult, however, since only two studies directly compare these two sectors.

Methodologies used for impact assessments are often those associated with LCA, allowing for a relatively good coverage of possible impacts, sometimes complemented by specific modeling tools – for example, biophysical processes for soil impacts or economic models for the determination of indirect LUC. Despite the widespread use of LCA, modeling choices are not necessarily uniform. For example, indirect LUC are not considered in four studies despite replacements of arable crops; indirect LUC are almost never considered where grasslands are replaced; and three articles make very specific assumptions with respect to the use of abandoned, contaminated, or saline soils in direct LUC. These methodological differences make it challenging to compare results across different studies, particularly in the evaluation of GHG emissions. The lack of diversity in methodologies also raises a concern that any methodological biases related to the use of LCA are unlikely to be balanced out across the literature sample. Because they are static and centered on a specific sector, LCAs cannot satisfactorily incorporate certain system features, including the possibility of replacement by other systems as determined by a maximization of overall economic value; potential supply-chain deficiencies; technical innovations; changes brought about by price variations; or changes in the carbon and energy content of fossil-fuel based reference products. All of these features can potentially play a role in the evaluation of the exhaustion of fossil resources.

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## Annex: References in the Study Corpus Addressing Impacts on Nonrenewable Resources

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# Chapter 10
# Mapping the Evidence on the Environmental Impacts of Land-Use Change for Non-food Biomass Production

**David Makowski**

**Abstract** The environmental impact of land-use change for biomass production is controversial, and it is crucial to provide stakeholders with a reliable description of the existing evidence on this topic. In this paper, we use an emerging research synthesis method called “evidence mapping” to summarize the main characteristics of 241 studies in a graphical user-friendly format. Results showed that most of the reviewed studies were located in Northern and Southern Americas, especially in USA and Brazil. A majority of studies focused on 1G and 2G biofuel, and on electricity production. The impacts on greenhouse gas emission, soil carbon content, soil erosion, water consumption, and water eutrophication were frequently assessed in the selected group of studies. The evidence maps produced in this paper revealed that only few studies were conducted to analyse the environmental impact of land-use change for methane production, for wood production, and for the chemical industry. Only few studies assessed the impact on biodiversity, on air quality, on human health, and on waste induced by land-use changes for biomass production. Our results thus highlight major gaps of knowledge and future research needs on the land-use-mediated implications of the bioeconomy.

**Keywords** Biomass · Biofuel · Environmental impact · Evidence map · Greenhouse gas · Land use · Research synthesis

## 10.1 Introduction

A large diversity of biomass products has been considered as a source of renewable energy (Laurent et al. 2015). Hundred or even thousands of studies were published to evaluate the environmental impacts of land-use changes induced by biomass production (Fargione et al. 2008; Lopez-Bellido et al. 2014; Mueller et al. 2011,

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Robertson et al. 2008). These studies differ on several aspects, especially on their geographical locations, on the nature of the produced biomass (e.g., first generation vs. second generation), on the type of energy produced from biomass (heating, electricity, biofuels), on the types of land-use changes induced by biomass production (e.g., deforestation, substitution of pastures for arable crops), and on the environmental impacts assessed (e.g., greenhouse gas emissions, soil organic matter) (Berndes et al. 2013; Cherubini et al. 2009; Crutzen et al. 2008; Rowe et al. 2009).

Because of the large number of studies dealing with this topic, it is difficult to quickly identify well-studied areas or to highlight important gaps in knowledge. Without the help of formal research synthesis methods, it is thus not straightforward to determine which types of energy were the most frequently studied, which geographical areas were considered, and what kind of environmental impacts were assessed in the literature. Our inability to produce a synthetic view of the existing knowledge has important consequences. Without a clear picture of what is known and unknown, it is difficult to guide the prioritization of research and, also, to support decision making on an objective basis (McKinnon et al. 2015).

When a scientific topic appears controversial, it is crucial to provide stakeholders with a reliable description of the existing evidence. Several research synthesis methods are now frequently used to review evidence published in scientific journals. Among these methods, the two most popular are probably the systematic review and the meta-analysis (Chalmers et al. 2002). The former aims at collecting and appraising all relevant studies dealing with a pre-specified topic, while the later summarizes quantitatively a large number of studies using statistical methods.

While very useful, these two approaches do not always succeed in showing at a glance the areas that have been studied most and those that have rarely or never been explored. Evidence mapping is a recent method for synthetizing scientific studies (Miake-Lye et al. 2016). An evidence map is "a systematic search of a broad field to identify gaps in knowledge and/or future research needs that presents results in a user-friendly format, often a visual figure or graph, or a searchable database" (Miake-Lye et al. 2016). In a recent paper, McKinnon et al. (2015) recommended scientists and stakeholders to apply evidence mapping on topics central to sustainable development, such as renewable energy. The objective of this paper is to apply evidence mapping to a large set of studies assessing the environmental impacts of land-use change for biomass production.

## 10.2 Method

### *10.2.1 Systematic Review and Study Selection*

A systematic literature search was performed using the Web of Knowledge and the database of the Centre for Agricultural Bioscience (05/02/2015) according to the procedure described in Réchauchère et al., Chap. 1, this volume). The number of paper was equal to 5730. This set of papers was screened by using a textual analysis method (CorText, www.cortext.net). Results were used to define eight different clusters as explained in details in El Akkari et al., Chap. 2, this volume. The titles and abstracts of the references included in the cluster focussing on biomass production (1785 articles) were read by several experts. All papers that did not assess the environmental impacts of land-use changes induced by biomass production were removed, and 614 papers were selected at this stage. The full texts of the 614 papers were read by several experts, 241 papers were finally selected. Several key elements of these papers were extracted and put in a spreadsheet table as explained in Réchauchère et al., Chap. 1, this volume. This table was then used to build the evidence maps, as explained below.

### *10.2.2 Evidence Mapping*

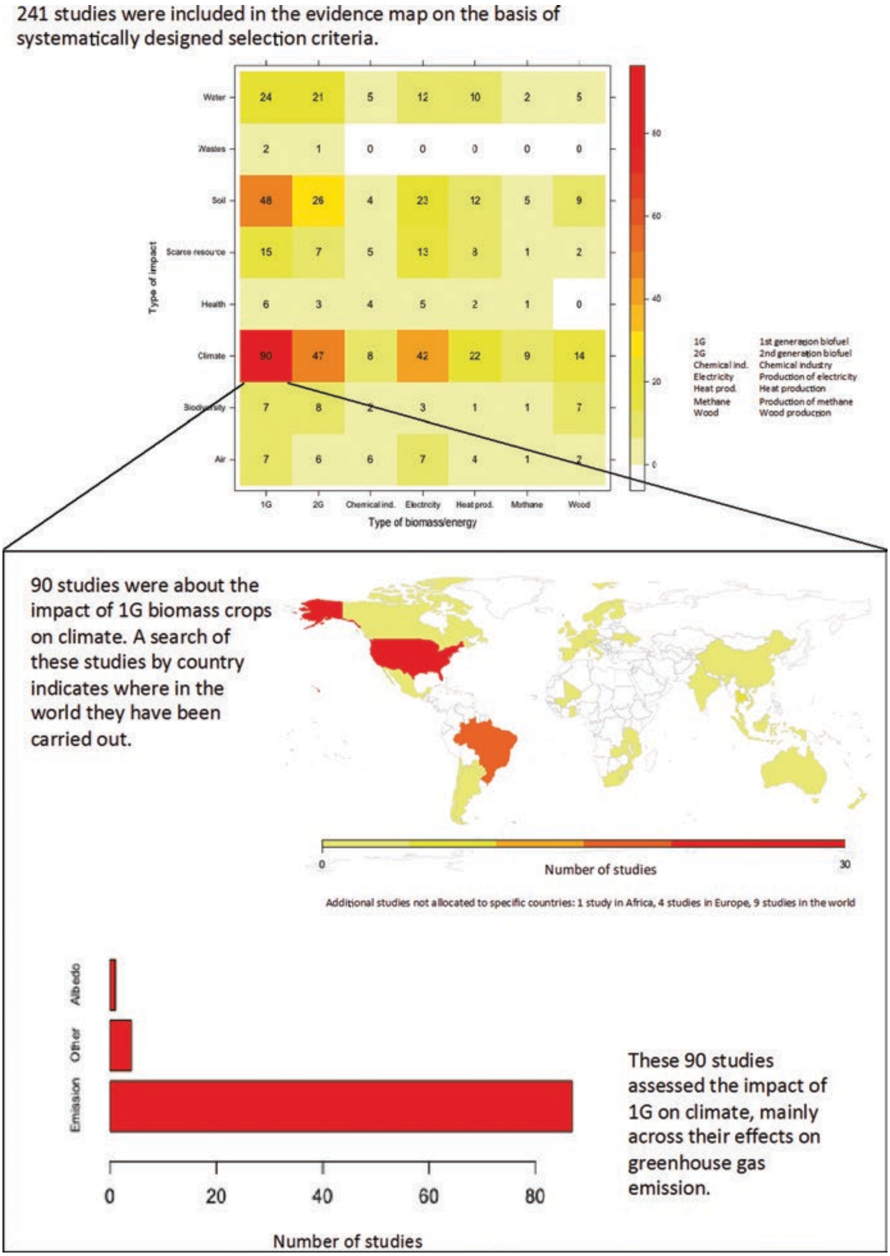
Studies were allocated to seven types of biomass uses (wood, biofuel 1st generation, biofuel 2nd generation, methane, chemical industry, heat production, electricity production) and to eight types of environmental impacts (soil, water, air, biodiversity, human health, climate, resources, wastes generation and disposal). The combinations of biomass uses and of environmental impacts led to 56 study categories. The number of studies falling in each category (i.e., biomass use/impact combination) was calculated. These numbers were then presented in a graphical contingency table.

Evidence maps were produced for the six most frequently studied combinations of biomass use and impact. Each evidence map was built by assembling three components; (i) the contingency table described above, (ii) a barplot describing the number of papers assessing the environmental impacts of biomass production according to several criteria, and (iii) a geographical map showing the number of studies by countries. Each map includes also three short pieces of text highlighting the main conclusions. This structure is very similar to the layout presented in McKinnon et al. (2015).

The evidence maps were produced using the R software (https://cran.r-project.org/). The contingency table was presented graphically using the function levelplot of the R package lattice. The barplots were built with the function barplot. The geographical maps were drawn using the functions joinCountryData2Map and mapCountryData of the R package rworldmap. The R codes used to produce evidence maps are presented in appendix A.

## 10.3 Results-Discussion

Among the 56 categories of studies considered in this paper (seven types of biomass x eight types of environmental impact), the six most frequently studied categories were “Impact of 1G biofuel on climate” (90 studies), “Impact of 1G biofuel on soil” (48 studies), “Impact of 2G biofuel on climate” (47 studies), “Impact on climate of electricity production from biomass” (42 studies), “Impact of 2G biofuel on soil” (26 studies), and “Impact of 1G biofuel on water” (24 studies). An evidence map was produced for each of these categories (Figs. 10.1, 10.2, 10.3, and 10.4).



241 studies were included in the evidence map on the basis of systematically designed selection criteria.

| Type of impact | 1G | 2G | Chemical ind. | Electricity | Heat prod. | Methane | Wood |
|---|---|---|---|---|---|---|---|
| Water | 24 | 21 | 5 | 12 | 10 | 2 | 5 |
| Wastes | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| Soil | 48 | 26 | 4 | 23 | 12 | 5 | 9 |
| Scarce resource | 15 | 7 | 5 | 13 | 8 | 1 | 2 |
| Health | 6 | 3 | 4 | 5 | 2 | 1 | 0 |
| Climate | 90 | 47 | 8 | 42 | 22 | 9 | 14 |
| Biodiversity | 7 | 8 | 2 | 3 | 1 | 1 | 7 |
| Air | 7 | 6 | 6 | 7 | 4 | 1 | 2 |

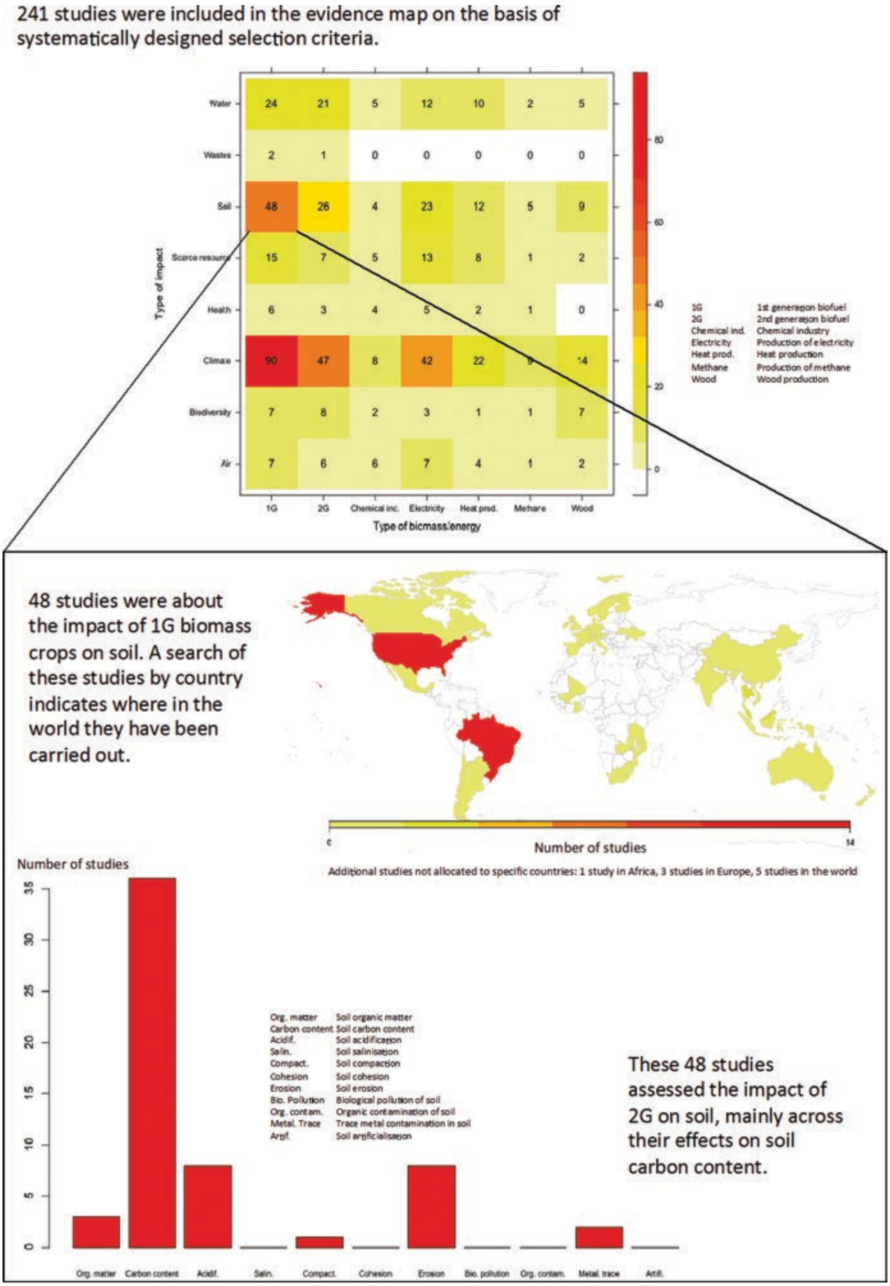
| | |
|---|---|
| 1G | 1st generation biofuel |
| 2G | 2nd generation biofuel |
| Chemical ind. | Chemical industry |
| Electricity | Production of electricity |
| Heat prod. | Heat production |
| Methane | Production of methane |
| Wood | Wood production |

90 studies were about the impact of 1G biomass crops on climate. A search of these studies by country indicates where in the world they have been carried out.

Additional studies not allocated to specific countries: 1 study in Africa, 4 studies in Europe, 9 studies in the world

These 90 studies assessed the impact of 1G on climate, mainly across their effects on greenhouse gas emission.

**Fig. 10.1** Evidence map of the impact on climate of land-use change for 1G biofuels



241 studies were included in the evidence map on the basis of systematically designed selection criteria.

| Type of impact | 1G | 2G | Chemical inc. | Electricity | Heat prod. | Methane | Wood |
|---|---|---|---|---|---|---|---|
| Water | 24 | 21 | 5 | 12 | 10 | 2 | 5 |
| Wastes | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| Soil | 48 | 26 | 4 | 23 | 12 | 5 | 9 |
| Scarce resources | 15 | 7 | 5 | 13 | 8 | 1 | 2 |
| Health | 6 | 3 | 4 | 5 | 2 | 1 | 0 |
| Climate | 90 | 47 | 8 | 42 | 22 | 9 | 14 |
| Biodiversity | 7 | 8 | 2 | 3 | 1 | 1 | 7 |
| Air | 7 | 6 | 6 | 7 | 4 | 1 | 2 |

| | |
|---|---|
| 1G | 1st generation biofuel |
| 2G | 2nd generation biofuel |
| Chemical ind. | Chemical industry |
| Electricity | Production of electricity |
| Heat prod. | Heat production |
| Methane | Production of methane |
| Wood | Wood production |

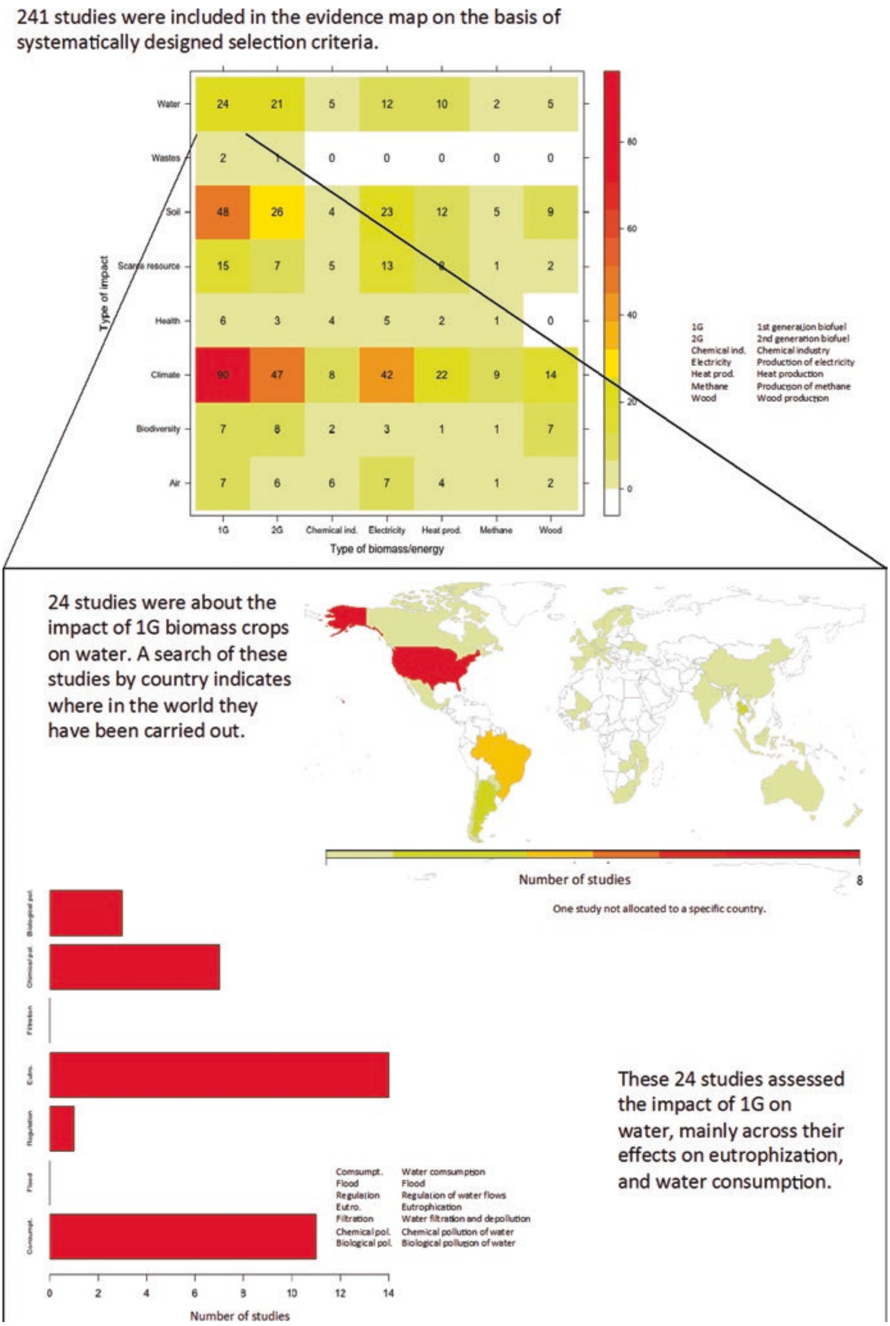
48 studies were about the impact of 1G biomass crops on soil. A search of these studies by country indicates where in the world they have been carried out.

Additional studies not allocated to specific countries: 1 study in Africa, 3 studies in Europe, 5 studies in the world

| | |
|---|---|
| Org. matter | Soil organic matter |
| Carbon content | Soil carbon content |
| Acidif. | Soil acidification |
| Salin. | Soil salinisation |
| Compact. | Soil compaction |
| Cohesion | Soil cohesion |
| Erosion | Soil erosion |
| Bio. Pollution | Biological pollution of soil |
| Org. contam. | Organic contamination of soil |
| Metal. Trace | Trace metal contamination in soil |
| Artif. | Soil artificialisation |

These 48 studies assessed the impact of 2G on soil, mainly across their effects on soil carbon content.

**Fig. 10.2** Evidence map of the impact on soils of land-use change for 1G biofuels

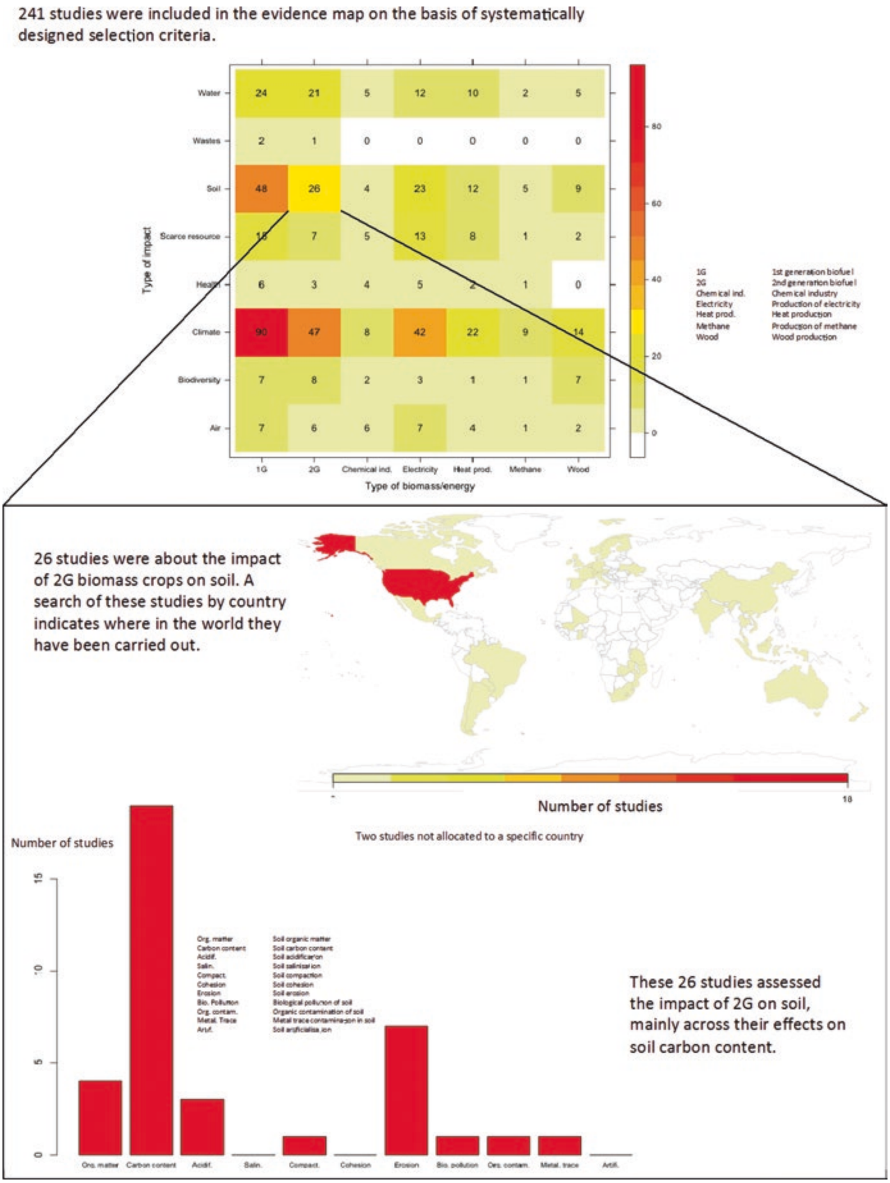


241 studies were included in the evidence map on the basis of systematically designed selection criteria.

24 studies were about the impact of 1G biomass crops on water. A search of these studies by country indicates where in the world they have been carried out.

These 24 studies assessed the impact of 1G on water, mainly across their effects on eutrophization, and water consumption.

**Fig. 10.3** Evidence map of the impact on water of land-use change for 1G biofuels



241 studies were included in the evidence map on the basis of systematically designed selection criteria.

| Type of impact | 1G | 2G | Chemical ind. | Electricity | Heat prod. | Methane | Wood |
|---|---|---|---|---|---|---|---|
| Water | 24 | 21 | 5 | 12 | 10 | 2 | 5 |
| Wastes | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| Soil | 48 | 26 | 4 | 23 | 12 | 5 | 9 |
| Scarce resource | 18 | 7 | 5 | 13 | 8 | 1 | 2 |
| Health | 6 | 3 | 4 | 5 | 2 | 1 | 0 |
| Climate | 90 | 47 | 8 | 42 | 22 | 9 | 14 |
| Biodiversity | 7 | 8 | 2 | 3 | 1 | 1 | 7 |
| Air | 7 | 6 | 6 | 7 | 4 | 1 | 2 |

| | |
|---|---|
| 1G | 1st generation biofuel |
| 2G | 2nd generation biofuel |
| Chemical ind. | Chemical industry |
| Electricity | Production of electricity |
| Heat prod. | Heat production |
| Methane | Production of methane |
| Wood | Wood production |

26 studies were about the impact of 2G biomass crops on soil. A search of these studies by country indicates where in the world they have been carried out.

Two studies not allocated to a specific country

| | |
|---|---|
| Org. matter | Soil organic matter |
| Carbon content | Soil carbon content |
| Acidif. | Soil acidification |
| Salin. | Soil salinisation |
| Compact. | Soil compaction |
| Cohesion | Soil cohesion |
| Erosion | Soil erosion |
| Bio. Pollution | Biological pollution of soil |
| Org. contam. | Organic contamination of soil |
| Metal. Trace | Metal trace contamination in soil |
| Artif. | Soil artificialisation |

These 26 studies assessed the impact of 2G on soil, mainly across their effects on soil carbon content.

**Fig. 10.4** Evidence map of the impact on soils of land-use change for 2G biofuels

Clearly, the evidence maps indicate that the emphasis of the scientific literature was mainly put on 1G and 2G biofuels, and on their impacts on climate and soils. However, a substantial number of studies focused on the use of biomass for electricity production and on its impact on climate and soils. Impact on water was also assessed in a relatively large number of studies. Impact on waste, health, air, and biodiversity were only rarely studied in the literature (Fig. 10.1). Only few studies assessed the environmental impacts of land-use change for methane production (Fig. 10.1). The environmental impacts induced by wood production and by the chemical industry were also rarely studied (Fig. 10.1).

Studies were spread over all continents, but most of the studies were located in Northern and Southern America, especially in USA and Brazil (Figs. 10.1. 10.2, 10.3, and 10.4). The numbers of studies conducted in Europe and Asia were smaller, and only a few studies were located in Africa (Western Africa and South-Eastern Africa) (Figs. 10.1, 10.2, 10.3, and 10.4). In most cases, the country showing the highest number of studies was USA. There was one exception: for the category "Electricity/climate", the highest number of studies pertained to Brazil. Several studies were not located in a specific country but in larger areas (e.g., Europe, Africa).

Greenhouse gas emissions were very frequently used to assess the impact on climate of land-use change for 1G biofuels, 2G biofuels, and bio-electricity (Fig. 10.1). The impact of biomass production on surface albedo, a biophysical parameter relevant to the climate/land-use interaction (Davin and De Noblet-Ducoudré 2010), was rarely assessed, i.e., in less than five studies per category (Fig. 10.1). Soil carbon content was frequently considered to assess the impact on soils of land-use change for 1G biofuels. However, other soil characteristics were also considered in a substantial number of studies, especially soil erosion and soil acidification (Fig. 10.2, Fig. 10.4). Other criteria for the impact on soil quality (e.g., organic matter, soil compaction, metal trace in soil) were considered in less than five studies per category (Fig. 10.2, Fig. 10.4). The impacts on water of land-use change for 1G biofuels was studied using a large number of criteria, especially eutrophication, and chemical pollution, but also water flux regulation and biological pollution (Fig. 10.3).

## 10.4 Conclusion

Most of the 241 studies considered in this paper pertained to bio-based value chains located in Northern and Southern America, especially in the USA and Brazil. A majority of studies focused on 1G and 2G biofuel, and on electricity production. The impacts on greenhouse gas emission, soil carbon content, soil erosion, water consumption, and water eutrophication were frequently assessed in the selected group of studies. The evidence maps produced in this paper revealed that only few studies were conducted to analyse the environmental impact of land-use change for biogas production, for wood production, and for the chemical industry. Only few studies assessed the impact on biodiversity, on air quality, on human health, and on wastes of land-use change for biomass production. Our results thus highlight major gaps of knowledge and future research needs.

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## Main Lines of R Code Used to Produce Evidence Maps

```
#Graphical contingency table (package lattice)
levelplot(NbArticles~as.factor(TypeProduit)*as.
factor(TypeImpact), xlab="Type of biomass/energy",ylab="Type of
impact",col.regions = heat.colors(100)[length(heat.col-
ors(100)):1], data=TABLEAU, panel=myPanel <- function(x, y, z, …)
{
panel.levelplot(as.factor(TypeProduit),as.factor(TypeImpact),NbAr
ticles,...)
panel.text(as.factor(TypeProduit),as.factor(TypeImpact),NbArtic
les)})
#Barplot
barplot(Crit,names.arg=c("Consumpt.","Flood","Regulation","Eutro.
","Filtration", "Chimical pol.","Biological pol."),horiz=T,col="r
ed",xlab="Number of papers",cex.names=0.7, main="Impact on water")
#Geographical map (package rworldmap)
map=joinCountryData2Map(dataCarte,joinCode ="ISO3", nameJoinCol-
umn ="Code")
map 1<-mapCountryData(map, nameColumnToPlot="NbArticles",addLegen
d=F,catMethod="pretty", mapTitle="Number of articles")
do.call(addMapLegend, c(map 1, legendWidth=0.5, legendMar = 10))
```

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